The Grip of Motorsport Surfaces

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I confirm that the word count of this thesis is less than 100,000 words

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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To my wife Sarah and daughter Isla. Thank you for your incredible support, for bearing with me and indulging my dream of playing around on racetracks!

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ABSTRACT

The following thesis is a body of work carried out over a six year period. The purpose of the work is to better understand racetrack grip. Research of this nature has never been conducted into evaluating the role of surface material as a component of grip in a racetrack environment. As such, this thesis is unique. This is highlighted through a rigorous literature review that emphasises the lack of academic research into the materials the makeup racetrack surfaces. Discussions with motorsport industry figureheads and governing bodies such as Federation Internationale De l'Automobile (FIA), Formula 1 (F1) and F1 teams confirmed that little is known about the surface aspect of the tyre/surface interface.

An evaluation of literature utilising existing skid resistance/grip testing methodologies commonly used on roads and airports indicated the potential benefits of using GripTester for evaluating the variation and evolution of racetrack grip. A micro GripTester push device was selected for focused grip testing and Close Range Photogrammetry (CRP) was shown to have the ability to create in-depth surface models to infer micro and macro roughness parameters.

A method for measuring racetrack grip, known as GripMap, is outlined. The process involves measuring wet grip over an entire track by completing multiple full laps at metre increments across the width of the track. This generates large datasets ranging from 20,000 to 80,000 discrete measured grip data samples. The Global Positioning System (GPS) stamped grip data can then be analysed as a whole using techniques such as cumulative frequency analysis or visualised as a map. The grip data can be created into a detailed GripMap using software such as Esri AcrGIS. This can be queried and analysed using colour threshold classifications to highlight features in the data such as the racing line, surface material changes, surface treatments and the build-up of contaminants such as rubber.

Unparalleled access to live top level motorsport events allowed for the selected process to be implemented during F1 and British Tour Car Championship (BTCC) events. The resultant data shows the ability of the GripMap system to capture variation and evolution of grip. The formation of the racing line, effect of rain on a

track surface, effect of surface treatments, highlighting low grip materials and evolution of grip is visible in the GripMap analysis. The benefit of focused grip evaluation surveys using a micro GripTester is illustrated. Smaller GripMaps can be created to measure grip in areas of interest that could help improve vehicle performance or prepare a racetrack for an event. A combination of the three methodologies provided a strong basis for analysing racetrack surfaces and variation in grip.

The 3D surface models created using CRP in this thesis produces significant findings. Analysis suggests that the enveloping of surface by an F1 tyre can be inferred using CRP. Surface models produced showed that the surface penetration of a F1 tyre at the Singapore Grand Prix 2017 and Singapore Grand Prix 2018 was 1mm and 1.8mm respectively.

This study and its findings suggests a set of conclusions and recommendations. Findings including detailing methodologies for measuring racetrack grip. This can be used for motorsport teams to improve performance and improving simulations. The opportunity to improve safety in motorsport through the creation of a homogenised approach to racetrack surfaces is discussed. A governing standard for racetrack surfaces and the adoption of the GripMap process as a tool for surface quality evaluation is recommended. The utilisation of the methodologies outlined in this thesis could improve the standard of racetrack surfaces and offer governing bodies the ability to assess surfaces before events for the improvement of safety standards.

LIST OF ABBREVIATIONS

ABS	Anti-locking Braking System
AC	Asphalt Concrete
AFC	Abbot-Firestone Curve
ASTM	American Society for Testing and Materials
AWS	Automatic Watering System
BPT	British Pendulum Tester
BS	British Standard
BTCC	British Tour Car Championship
CAD	Computer Aided Drawing
CCD	Charged Coupled Device
CFME	Continous Friction Measuring Equipment
COTA	Circuit of the Americas
CRP	Close Range Photogrammetry
CSV	Comma Seperated value
DFT	Dynamic Friction Tester

DRMB	Design Manual for Roads and Bridges
EFI	European Friction Index
ESRI	Environmental and Social Research Institute
ETD	Estimated Texture Depth
F1	Formula One
FAP	Friction After Polishing
FIA	Fédération Internationale de l'Automobile
FIM	Fédération Internationale de Motorcyclisme
FN	Friction Number
GIS	Geographic Information System
GMC	GripMap Corridor
GMM	GripMap Method
GN	GripNumber
GPS	Global Positioning System
GT	GripTester
GT	Grand Tourer

HRA	Hot Rolled Asphalt
ICAO	International Civil Aviation Organization
ID	Identification
IFI	International Friction Index
LCD	Liquid Crystal Display
LTA	Land Transport Authority (Singapore)
LTS	Laser Texture Scanner
micro GT	micro GripTester
MPD	Mean Profile Depth
MSA	Motor Sports Association
MTD	Mean Texture Depth
NGTC	Next Generation Touring Car
PMB	Polymer Modified Bitumen
PSV	Polished Stone Value
RMS	Root Mean Square
RTK	Real Time Kinetic

SBS	Styrene Butadiene Styrene
SCANNER	Surface Condition Assessments of National Network of Roads device
SCRIM	Sideways-force Coefficient Routine Investigation Machine
SFC	Sideways-force Coefficient
SGP	Singapore Grand Prix
SKM	Sideway-force Traction Measurement System
SLR	Singe Lens Reflex
SMA	Stone Mastic Asphalt
SN	Skid Number
SQL	Structured Query Language
SR	Skid Resistance
SRT	Pendulum
TIN	Triangular Irregular Networks
TPI	Texture Profile Inex
TRL	Transport Research Laboratory

UK	United Kingdom
UK CAA	United Kingdom Civil Aviation Authority
USB	Universal Serial Bus
VW	Volkswagon
WRX	World Rally Cross

GLOSSARY OF TERMS

Term	Definition with respect to this thesis
Adhesion	The coefficient of the molecular interaction of a tyre with the microtexture of a surface
ArcGIS	Geographic Information System software suite by Esri
ArcMap	Map creation software program that is part of the Esri ArcGIS suite
Bitu-planing	Vehicle loss of traction as a result of excess bitumen on the racetrack surface
Bulk Hysteresis	The loss of energy from the deformation of the tyre surface as it interacts with the macrotexture
Coefficient of friction	A measured value that shows the relationship between the force of friction between two objects such as tyre rubber and a racetrack surface
Cohesion	A measure of the forces holding materials together
Commercial rights holder	The organisation that holds the commercial rights from the governing body to market a racing series
Cruise control	A driver aid that computer controls a vehicles throttle to maintain a constant set speed
Dry grip	GripTester data measured under dry conditions
Enveloping	How the rubber of a tyre penetrates the surface texture of a racetrack
Friction	The resistance that one surface or object encounters when moving over another
Governing body	The overriding motorsport legislator e.g. FIA or FIM
Green track	How the grip of a race course is cleansed by rain
Grid box	The starting position of an individual vehicle on a racetrack starting grid
Grid	The starting formation of a race, generally in rows of two for cars and three or four for bikes
GripMap	A map of a racetrack showing longitudinal and lateral variation in grip

GripMap Corridor	The area of track where most tyre / surface interaction occurs approximately 4 m wider than the racing line for car racing and 2 m wider for motorcycle racing
GripMap Method	A method for mapping a racetrack showing longitudinal and lateral variation in grip under standardised test conditions
GripNumber	The co-efficient of friction produced by the GripTester
High pressure water retexturing	A system of using high pressure water through targeted nozzles to clean, remove bitumen or debris from a racetrack surface
Hydroplaning	Loss of vehicle traction and sliding due to a film of water between the tyre and race track surface
Marbles	Debris from tyre rubber found on the race track surface
Macrotexture	The surface void around racetrack surface aggregate particles
Mean texture depth	A measure of macrotexture determined using the Volumetric Patch Technique
Microtexture	The texture or irregularities on the surface of an aggregate particle
Practice	A non-competitive motorsport testing session
Qualifying	The process of deciding the starting order of a race
Race Director	An official appointed by a series organiser who holds ultimate authority over race operations throughout every event of a championship
Racetrack/Race Circuit	A controlled area where motorsport activities take place
Racing line	The optimum way around a racetrack
Roughness	An expression of irregularities in the pavement surface that adversely affect the ride quality of a vehicle
Rubbered in	The process of the rubber being deposited on the racetrack surface which alters the tyre / surface contact making the racetrack lap times faster

Simulation	The use of computers and data to replicate racing, vehicle or tyre parameters in a virtual environment
Skid resistance	The force developed when a tyre that is prevented from rotating as it slides along a road or airport surface
Starting grid	The starting formation of a race, generally in rows of two for cars and three or four for bikes
Surface characteristics	The properties of a racetrack surface which include texture and material components
Traction	The power supplied to the wheels of a vehicle and its ability to achieve velocity from tyre / surface contact
Tyre compound	Description of the hardness of rubber used in the construction of tyre running surface
Tyre manufacturer	The provider of race tyres for a racing series
Vehicle dynamics	How a vehicle will react to driver inputs on a racetrack which includes the effect of suspension, tyres, drivetrain, aerodynamics, steering and braking
Wet grip	GripTester data measured under wet conditions

ACCESS TO CONTENTS

CHAPTER 1

INTRODUCTION

1 Chapter 1: Introduction

1.1 Introduction

This thesis considers the grip of motorsport surfaces. Differing terminology is used to describe the interaction between a vehicle and surface. Skid resistance or friction is typically used in the road and airport industries. The term grip is commonly used throughout the motorsport industry. This thesis uses the generic term grip as it is concerned with motorsport surfaces.

Grip is discussed at all levels and types of motorsport. Meetings with race teams such as Mercedes AMG Petronas F1 and Formula One confirmed that whilst motorsport stakeholders collect extensive data about the vehicle it would appear, they seem to know little about the surface on which they race.

During a meeting with Charlie Whiting, FIA Formula One Race Director at the Singapore Grand Prix in September 2018, discussed the need for homogenisation of racetrack surfaces. Based on this conversation, it appears that the FIA intends to begin a technical process to achieve this as a medium-term objective. However, it is difficult to satisfy the requirements of grip for all the different stakeholders.

The FIA want a safe, high grip surface that is consistent. F1 want a high grip surface that will cause high tyre wear and consistent tyre degradation to produce exciting racing with pit stops. Race teams want a consistent, predictable surface that helps with car setup and tyre selection. Racetrack operators want a maintainable, long lasting, lower grip surface. Therefore, achieving a better understanding of racetrack surface characteristics and quantifying their variation would benefit the entire motorsport industry.

Motorsport places ever-increasing emphasis on computer simulation and use of full-scale simulators to fast-track development, vehicle setup and reduce costs. Presentations at the 2018 VI-grade Users Conference from major vehicle and tyre manufactures highlighted the importance of improving simulations and correlations in the virtual environment to that of real life. A number of presentations considered grip but further discussions revealed that in most simulation datasets the test track surface grip was assumed to be constant. The ability to measure and better understand grip and other surface characteristics would contribute significantly to more realistic models and simulations.

Currently, there is no method used in motorsport to measure racetrack surface characteristics such as grip in a standardised way similar to that used on road and runway surfaces. The mandatory measurement of grip and legislated minimum grip levels have been in place for airports and roads for many years (Yager, 1997). Research into grip in the UK dates back to the 1930s with legislation based on well-established underpinning knowledge introduced over 40 years ago. However, a level of wet grip that is considered low on a road or airport would be considered high grip by racing drivers in dry conditions. This must be taken into account when considering a standardised method of measuring grip.

This thesis illustrates how existing knowledge from the road and runway can be transferred to motorsport. It describes the development of a method to test motorsport circuits in a standardised way presented in this thesis as the GripMap Method (GMM). Similar to roads and runways this is a standard method. Unlike roads which typically measures just the inside wheel path, the GMM measures the entire track surface both longitudinally and laterally with individual grip measurements recorded on a nominal 1m x 1m grid. This allows mapping of what has been termed the GripMap Corridor (GMC).

The mapping of grip at this scale shows a distinct corridor going around a circuit where the grip levels are most susceptible to variation. This corridor approximates to the racing line and depending on specific circuits and events will be modified depending on what vehicles are using the track. It is proposed that the GMM has the potential to impact motorsport in a range of areas including safety, simulation, racetrack surface design, race team operations and targeted track maintenance.

1.2 Background

Motorsport is competitive and secretive. Data related to vehicles, tyres or racetrack surfaces is difficult to obtain due to commercial sensitivities. The difference between competing cars and bikes in motor sport is frequently measured in 10ths or 100ths of a second. Despite these challenges, it was possible to use data in this thesis measured at three tracks, Knockhill Racing Circuit Scotland; Yas Marina Circuit Abu Dhabi and the Marina Street Circuit Singapore.

Knockhill is an example of a typical UK track used for a wide range of motorsport events. It was used as an outdoor laboratory. Testing at Yas Marina was at the invitation of Abu Dhabi Motorsport Management. This was the first time the GMM test method was used overseas. It tested logistical aspects of the operation.

The Singapore testing was at the invitation of Singapore Grand Prix (SGP) and carried out in 2017 and 2018. The Singapore testing allowed access to the different types of track surface preparation leading up to and during practice, qualifying and the street circuit F1 race itself.

Data from these three circuits are used as examples in this thesis. Due to commercial reasons much of the early GMM development cannot be included. This dates back to November 2007 when a GripTester was first used to measure the before and after effects of treating a track to improve its wet grip. This found variation in wet grip around the track to vary significantly and more extensively than for a typical road or runway. This has been demonstrated in all wet grip testing at every circuit since.

It was thought that this related to what the cars and bikes were doing within the track's racing line. Compared to roads there are significant differences in acceleration, braking, cornering and the tyres being used. An asphalt mix taken from a road would be subject to these extreme conditions and react accordingly. Once a road is open it will through time and trafficking reach what is termed equilibrium in terms of grip. With continued use there will be some variation in wet grip over a period of a year, depending mainly on seasonal environmental factors.

The differences in wet grip found for different tracks suggests that equilibrium also applies and explains how a track may be called green and gets quickly rubbered in improving lap times accordingly. The surfacing of a track is much more susceptible to change compared to the same material used as a road surface. The use of GPS to measure track position during testing allowed grip data to be plotted as a map.

Subsequent testing across the UK, mainland Europe and overseas has found all tracks to behave in a similar manner with respect to grip. The GripMap Method allows them to be measured in a standardised way. Every track has a distinct GripMap Corridor where the majority of change takes place.

1.3 Thesis Aim, Objectives and Research Questions

The aim of this thesis is to better understand the variation and evolution of racetrack grip and related surface characteristics using what has been termed the GripMap Method (GMM).

The thesis has the following objectives:

- Critically appraise the literature and ascertain the perspectives of motorsport governing bodies and stakeholders to identify knowledge gaps.
- Evaluate and select appropriate testing resources.
- Design a test method to measure grip.
- Apply the test method to the motorsport environment.
- Evaluate the validity of the test method and the output data to the motorsport industry.
- Propose a test method for the benefit of different motorsport stakeholders.

The thesis addresses the following research questions:

- Is there a need for a method to quantify grip for a racetrack?
- Can a standard method be developed to quantify and map grip on racetracks?
- What are the practical applications?
- How can the method be used to provide practical information relevant to motorsport?
- Can the method provide targeted grip data for localised areas of interest?
- Can tyre/surface interface parameters be related to grip?

1.4 Thesis Outline

The thesis has the following structure:

Chapter 1: Introduction

Chapter 2: Literature review

Chapter 3 Methods and Equipment for Data Capture

Chapter 4: The GripMap Method

Chapter 5: How to Analyse Measured Grip Data

Chapter 6: Measuring Localised Racetrack Grip Using Push CFME

Chapter 7: 3D Surface Texture Modelling and Combining Grip Measuring Techniques

Chapter 8: Discussions

Chapter 9: Conclusions

Chapter 10: Recommendations for Further Research

CHAPTER 2

LITERATURE REVIEW

2 Chapter 2: Literature Review

2.1 Introduction

In order to establish the factors that cause variation in racetrack grip it was important to critically appraise previous published work. The purpose of this chapter is to present a review of literature in order to identify knowledge gaps and raise research questions.

2.2 Classical Friction Theory

The history of understanding friction can be traced back to the earliest days of humankind. In the stone age, early man was grappling with friction by using the frictional heat created by rubbing stones together to create fire. Now known in physics as the science of tribology (taken from the Greek tribos meaning rubbing), this focuses on the mechanics and energy dissipation of moving parts as well as adhesion, lubrication, wear and friction (Bhushan, 1999).

The first conceptualisation of friction theory is attributed to Leonardo da Vinci who observed the effect of load and the interaction of the geometrical contact areas of two surfaces. Da Vinci's work on friction was lost for centuries and then resurfaced in Spain. Guilaume Amontons (1699) developed the ideas of da Vinci and published his first notes on friction in 1699. Other notable pioneers in the field were John Theophilius Desanguliers, Leonard Euler (1771) and Charles-Augustin Coulomb (1773). Their respected works were combined to give the three standard laws of friction:

1) Amontons' 1st law: the force of friction is directly proportional to the applied load (Amontons, 1699).
2) Amontons's 2nd law: the force of friction is independent of the apparent area of contact (Amontons, 1699).
3) Coulomb's law: kinetic friction is independent of the sliding velocity (Coulomb, 1773).

Amontons (1699) studied two plates made of different materials sliding across each other without lubrication when he came across the science of friction first conceptualised by da Vinci. The results of Amontons's experiments led to the belief that friction was the energy required to lift one surface over the roughness of another surface or from the wearing and damage caused by the weaker surface. Therefore, frictional force is the required energy to move one surface over another and the resultant loss of energy.

These experiments centred on kinetic friction rather than the static friction experiments observed by da Vinci. A distinction between static and kinetic friction was not made until the work of Leonard Euler (1771) who observed that increasing the angle of an inclined plain will not reduce the speed of the motion.

Coulomb's research into the fundamentals of friction confirmed Euler's theory through experiments which found that friction is independent of velocity after measuring kinetic friction at differing speeds. The key to Coulomb's work was highlighting the large number of variables that can affect friction (Bowden & Tabor, 1950).

The three fundamental laws of friction can be summarised by the following equation:

$$F \propto \mu L \qquad - (1)$$

where F is defined as the frictional force acting on two objects; L is the load experienced by the two surfaces being pressed together; μ is the coefficient of friction which depends on the type of materials in contact and whether they are stationary or in motion.

Coulomb also carried out work into rolling friction where he first suggested that the frictional resistance of a rolling wheel or cylindrical object is proportional to the applied load and inversely proportional to the radius of the wheel (Bowden & Tabor, 1950).

These basic laws of friction are concerned only with friction in dry conditions. Although the effects of lubrication on reducing friction had been known to man for centuries, most of the early work revolved around dry conditions until the late 18th century when Osbourne Reynolds (1886) observed the hydrodynamic nature of lubrication. This led to the creation of his fluid-film lubrication theory.

According to Coulomb's third law, kinetic friction is independent of the sliding velocity. Therefore the velocity of the moving surface is not dependent on velocity. However, this is only partially true in dry conditions. More accurate experiments found that friction in dry conditions decreases as velocity increases.

Frictional heating has been shown to be the energy dissipation expelled (Thruston, 1879). When lubrication is taken into consideration, Stribeck (1902) demonstrated that friction is influenced by a fluid being present between two surfaces in which the film prevents the surfaces from fully contacting each other thereby reducing the friction co-efficient. His experiments using rotary bearings distinguished three friction regimes when sliding lubricated surfaces:

1) elasto-hydrodynamic lubrication (boundary friction).
2) mixed friction.
3) fluid friction.

This later became known as the Stribeck (1902) curve. It was not until the early 20th century when Bowden and Tabor (1950) carried out a significant volume of work in friction that some of the seeming contradictions in the three laws of friction were resolved. They demonstrated that surfaces which appeared smooth and solid were not perfectly flat, rather they are rough with peaks and troughs on a microscopic scale. They identified miniscule texture on the surface, termed asperities, which prevent two seemingly smooth surfaces from making 100% contact.

Contact is actually a large number of smaller contacts where atom-to-atom contact takes place. The true contact area is a vastly reduced percentage than what was initially conceived. It is proportional to the force experienced when two surfaces are in contact whereas friction is proportional to the real area of contact (Bowden and Tabor, 1950). Although this literature relating to friction is extensive it is not entirely relevant to this thesis which concentrates on better understanding of the race track surface and how it interacts with tyre rubber.

2.3 Friction Theory Involving Rubber

The frictional properties that combine to form the contact between a rubber tyre and racetrack/road surface are complex. Due to the unique chemical makeup of rubber and its viscoelastic properties the resultant reactions when it is slid across another surface are different to those of materials such as metal or wood.

Grosch (1963) attempted to identify rubber friction mechanisms by restricting and controlling variables by sliding different surfaces at varying speeds on a range of five rubber compounds. The rubber samples were loaded onto the moving surfaces with weights strung beneath them. The selected surfaces included waved glass, smooth and abrasive silicon carbide paper. In order to reduce friction and increase reproducibility, a glass surface that contained ripples or waves on the surface was selected over a smooth surface.

Grosch (1963) identified that the frictional heating of the samples would make the interpretation of the results unduly complicated. The sliding speed was reduced to 3cm per second to avoid this energy loss. Surfaces that were subjected to stress wear, such as silicon carbide, were only used once in order to increase the accuracy of the experiment. Temperature of the test samples, surface materials and rubber compounds were kept constant for all testing.

A reference temperature was applied as a master curve to the results allowing the measured rubber co-efficient of friction (μ) of the samples to be plotted against the testing surfaces' sliding speed. The observed data was considered to be a combination of all mechanisms of friction present. The results suggested that rubber friction on the abrasive, grit-based surfaces was primarily due to bulk deformation hysteresis. Further experiments supported the theory that adhesion and bulk deformation hysteresis could occur concurrently when rubber is involved.

Kummer (1966) considered four main factors to affect friction involving rubber i.e. adhesion, cohesion, viscous friction and hysteresis. They can be summarised as the principal components of adhesion and hysteresis losses. A generalised model for friction was proposed based on this work with regard to road tyre surface interaction. This states that two or more components in the model will combine to create the measured friction and that friction should be assumed to be caused by tyre/surface interaction as well as the noted losses.

This was a unified theory of rubber friction showing a relationship between the damping properties of rubber and the effects of adhesion and hysteresis. Further research in this area has confirmed Grosch’s (1963) work. Kummer (1966) defined the friction mechanism producing hysteresis in vehicle tyres as draping in which the rubber tyre is observed to drape over the protruding aggregate or surface particle when in contact with the surface.

Kummer (1966) offered a Unified Theory of Rubber and Tire Friction which combined and identified the individual components of the mechanisms involved in rubber friction for tyres. Figure 2-1 illustrates the model for mechanism of rubber friction according to Kummer (1966).

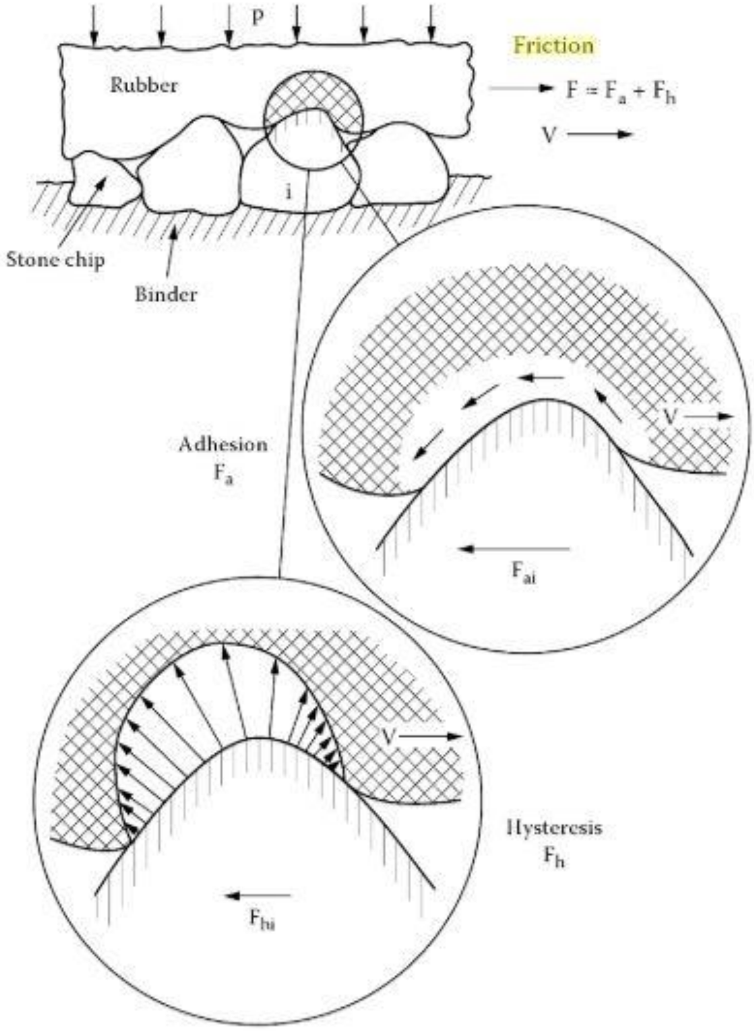


Figure 2-1 Model for mechanism of rubber friction (Kummer,1966)

Kummer (1966) proposed the following model:

$$F_T = F_A + F_{HB} + F_c \qquad - (2)$$

Where F_T is the frictional resistance from the contact of a dry road surface and rubber tyre sliding; F_A is representative of the adhesion between the two surfaces; F_{HB} is the frictional contribution from the bulk deformation hysteresis in the rubber; and F_c is the rubber wear which is related to the cohesion loss.

This hypothesised that F_A and F_{HB} cannot be considered independently of one another as adhesion can increase the contact patch and the rubber draping effect where hysteretic deformation is occurring.

Kummer (1966) stated that wear is incorrectly equated to friction, but is a special case of adhesive and abrasive wear exist. Adhesive wear is damage caused by the contact of two dissimilar material surfaces with the intrinsically harder material inserting itself causing damage, such as scoring or grooving. This is not necessarily proportional to friction due to the level of adhesion being unrelated to abrasion. Rubber wear or cohesion loss is relatively small amounting to 1-2% even on rough surfaces, compared to the proportion of the overall interaction in non-emergency braking (Kummer, 1966).

Adhesion at the tyre/surface interface can be summarised as the resultant friction from the small-scale bonding or interlocking of the vehicle tyre rubber and the surface as they interact (Hall et al., 2009). Figure 2-1 shows the accepted frictional force ascribed to adhesion (Kummer, 1966). Thirion (1946) pioneered the theory that the friction interaction experienced between a smooth surface and rubber is adhesion. The experiments demonstrated hyperbolic relationships between rubber and a smooth surface. It concluded that the co-efficient of friction of different rubber samples varies with the same load applied. Thirion (1946) concluded that friction was dependent on contact area.

This observation was developed by Schallamach (1952) who surmised that the friction force exerted by rubber is proportional to the true area of asperity contact with the surface it is in contact with. Contact area frictional force and the relationship with varying load is consistent with Hertz’s (Schallamach, 1952) equation for resultant contact areas formed due to elastic deformation when smooth surfaces are pressed together. By experimenting with different hardness of rubber compounds and varying loads, Schallamach (1952) hypothesised that adhesive friction must become asymptotically constant because the asperities cannot endlessly deform when affected by extreme loadings.

Understanding the contact between imperfect rough surfaces has been considered by many researchers including Lorenz et al (2010), Lu (2012), Carbone (2011), and Wang et al (2014) who carried out research surrounding the effect of multi-asperities in rubber contact with varying results regarding the contact area.

According to Kane et al. (2009) other theories suggest the tyre/surface interface adhesion is a result of molecules being thermally energised creating a stick-slip process. The two surfaces when in contact, cause the rubber molecule chains to attempt to bond to those of the harder surface. The sliding effect of the velocity causes the bonds to deform, stretch, break, relax and then attempt to form bonds again with the next contacted molecules.

Surface hysteresis friction in rubber has been considered to be the result of the micro-roughness of the harder material. Kummer (1966) stated that the harder surface micro-roughness is made up of microscopic peaks or asperities which interact with the rubber tyre in a cyclic deformation.

The adhesion and hysteresis components and their importance to the interaction between the rubber tyre and surface are largely dependent on the surface characteristics. The hysteresis component of friction is a result combined energy loss Kummer (1966). Kummer (1966) demonstrated that friction caused by hysteresis according to Coulomb’s (1773) third law of friction is not adhered to and is not independent of the sliding velocity.

2.4 Tyre/Surface Interaction

Different terms are used interchangeably when referring to the forces generated at the tyre/surface interface. Friction, in the context of tyres and roads is the force experienced by a particular vehicle tyre on a particular road surface at that instance in time (Kane, 2009). Grip is used in motorsport and is the term adopted throughout this thesis.

Both terms are influenced by a combination of factors such as vehicle dynamics, contaminants such as rubber; detritus and environmental factors at the specific time of a vehicle interaction.

The term skid resistance is typically used to describe the contribution of the road surface in the tyre/surface interface relationship. This is derived from data collected from a standardised testing method from devices such as Sideways-force Co-efficient Routine Investigation Machine (BS 7941-1:2006) or GripTester (BS 7941-2:2000).

These are examples of standardised Continuous Friction Measuring Equipment (CFME). These methods use a standardised measuring tyre under standardised operating testing conditions with test speed and water film depth closely controlled. Unless otherwise noted, skid resistance data relating to a road or runway is always measured under wet conditions.

These standardised methods produce a co-efficient of friction. For example, the GripTester device produces a GripNumber (GN) which is the mean of a number of friction readings over a defined length (BS 7941-2:2000).

The friction forces generated by a vehicle tyre in contact with a road surface can be summarised as the forces that resist the relative motion of the vehicle (Hall et al., 2009). A simplified model of the forces at the tyre/surface interface are illustrated in Figure 2-2.

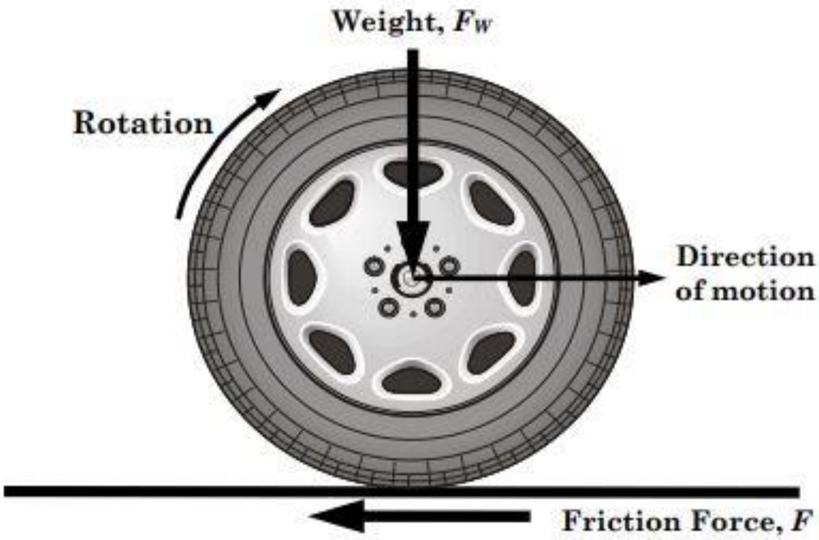


Figure 2-2 - Simplified illustration of tyre/surface interface forces of a moving wheel (Hall et al., 2006)

Hall et al. (2006) gave the following equation to represent the forces present as a vehicle tyre interacts with a road surface:

$$\mu = \frac{F}{Fw} \qquad - (3)$$

Where: the non-dimensional friction co-efficient μ is a ratio of the tangential friction force (F) between the tyre rubber and the horizontal travelled surface to the vertical load (Fw).

The role of road surface grip is fundamental in allowing the safe travel of vehicles, allowing the ability to brake, manoeuvre and corner effectively. This is important for roads, runways, racetracks and public highways. The greater the grip available at the point of contact between the road surface and vehicle tyre, the greater the level of control the driver should experience (Kane et al., 2009). However, with the advancement of vehicle technology regarding assisted braking systems, automated vehicles and driver assisted technology, this may become less important even in wet conditions. In the context of motorsport, the contribution of grip is important in safety terms and to maximise performance and optimising vehicle setup (Farroni et al., 2014).

According to Meyer (1982), a vehicle tyre will be subject to directional friction forces, longitudinal forces and lateral forces. Longitudinal frictional forces occur between the surface and the tyre when it is free-rolling or in constant braking (Hall et al., 2009). When free-rolling occurs, the slip speed is zero which is defined as the relative surface and full revolution of the tyre. The slip speed will increase from zero to the maximum speed of the vehicle when the vehicle is braking. A locked wheel when braking is considered to have 100% slip ratio.

The following equation was proposed by Hall et al. (2006) to calculate slip speed:

$$S = V - Vp + V - (0.68\ x\ \omega\ x\ r) \qquad - (4)$$

The following equation was proposed by Meyer (1982) to calculate the slip ratio:

$$SR = \frac{V - Vp}{V}\ x\ 100 = \frac{S}{V}\ x\ 100 \qquad - (5)$$

Where: S is the slip speed, V is the vehicle speed, Vp is the average peripheral speed of the tyre, ω is the angular velocity and r the average radius of the tyre.

The rolling resistance force is the force required to overcome the offset created by the centre pressure of the tyre/surface contact area irregularity and is important when considering the overall tyre/surface interface.

Andressen and Wambold (1999) presented the following diagrams which illustrate the forces acting on a tyre when free-rolling and braking. These are shown in Figure 2-3 and Figure 2-4.

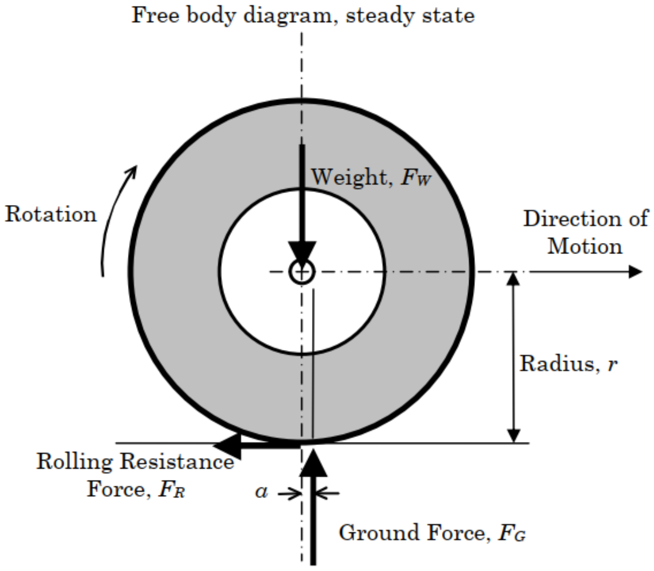


Figure 2-3 - Rolling resistance with a free-rolling tyre at a constant speed on a dry paved surface (Andressen and Wambold, 1999)

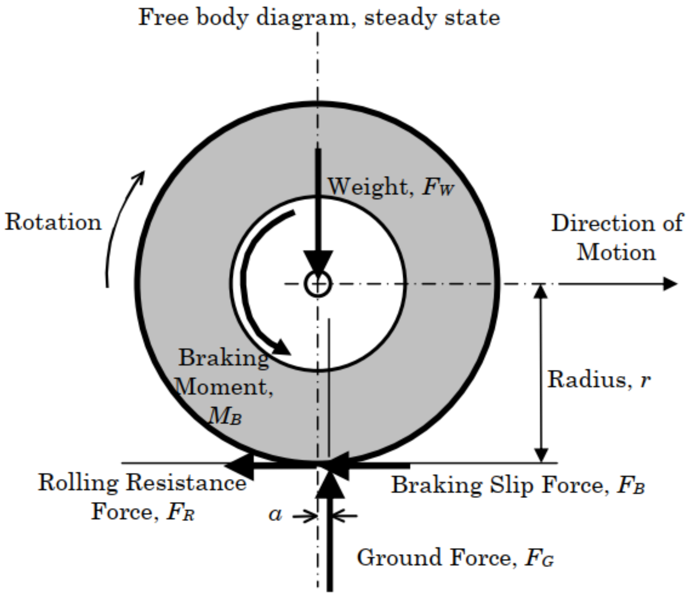


Figure 2-4 - Forces and moments of a constant braked wheel on a dry paved surface (Andressen and Wambold, 1999)

Henry (2000) developed the theories of Horne et al. (1968) and proposed that skid resistance or co-efficient of friction at the point of the tyre/surface contact varies depending on the slip. Figure 2-5 shows the theorised model where friction/grip level increases rapidly during braking to a peak level that usually occurs between 10% and 20% slip. This is also termed as the critical slip. Sliding with a fully locked wheel occurs at 100% slip. This model is based on dry conditions. An Anti-lock Braking System (ABS) is designed to keep the amount of slip near to peak friction to maximise braking performance. The difference between the peak friction and sliding levels is greater on wet surfaces compared to dry conditions (Hall et al., 2009).

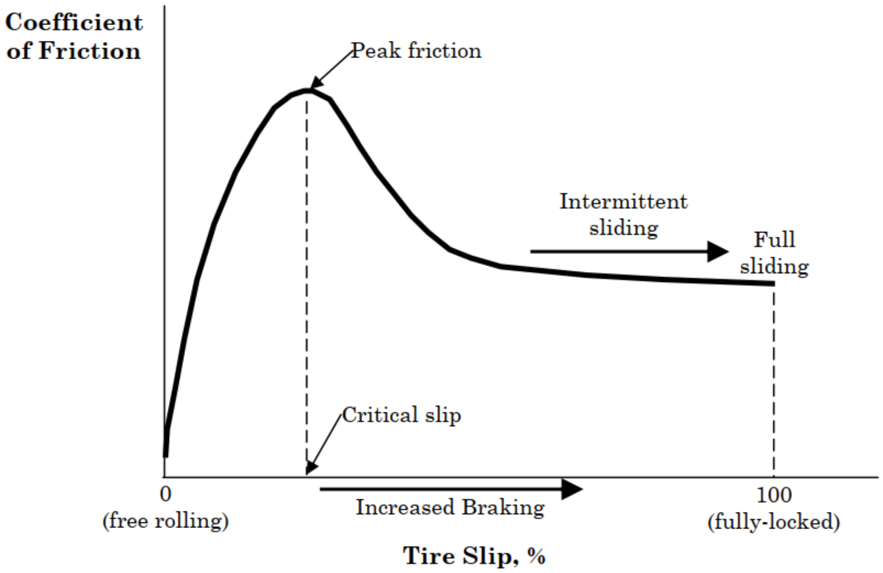


Figure 2-5 - Surface friction/grip versus tyre slip (Henry, 2002)

Hall et al,. (2008) asserts that this model is a misinterpretation of the laws of metallic friction which do not apply to rubber and the co-efficient of rubber friction is generally not constant under normal applied loads. Hall et al (2008) states that a reformulation of the tyre friction versus slip ratio relationship is required. This should utilise a unified theory of rubber friction that considers all the frictional forces arising from the unique properties of the viscoelastic material. This should be based on appropriate testing that considers the possible presence of micro hysteresis.

The lateral or side-force friction forces occur as a vehicle corners or as a result of road camber or environmental factors such as wind or turbulent air from another vehicle. The relationship between the forces acting on the tyre from contact with the surface were described by Hall et al (2006) as:

$$Fs = \frac{V^2}{15R} - e \qquad - (6)$$

Where: Fs is the side friction, V is the speed of the vehicle, R is the radius of the cure and e is the pavement super elevation.

Wallman et al. (2001) summarised work by Kummer (1966) to produce a table of factors which influence road surface friction. This was modified in the Guide for Pavement Friction NCHRP project (2009). This highlights the key parameters affecting friction or grip of a vehicle as it interacts with a road or racetrack surface.

Table 1 Factors influencing road surface friction (Wallman et al., 2001)

Road	Contaminant (fluid)	Tyre
Macrotexture	Chemical structure	Tread pattern design
Microtexture	Viscosity	Rubber composition
Unevenness/Megatexture	Density	Inflation pressure
Chemistry of materials	Temperature	Rubber hardness
Temperature	Thermal conductivity	Load
Thermal conductivity	Specific heat	Sliding velocity
Specific heat	Film thickness	Temperature
		Thermal conductivity
		Specific heat

2.5 Influence of Pavement Texture

The importance of road surface characteristics related to texture has been acknowledged for many years in the UK. The provision of appropriate levels of wet skid resistance, how it is measured, the data interpreted and how it is managed is given in HD26/15 (DMRB, 2015). It is complimented by CD 236 (DMRB, 2018) which sets out advice on the surfacing material characteristics necessary to deliver the required skid resistance properties.

Wet road skid resistance is affected by properties at different texture scales. Figure 2-6- Diagram of Texture Length and Depths (DRMB, 2015) is taken from HD26/15 and illustrates the different texture lengths and depths of a typical road surface. Different types of road surface and the asphalt or concrete materials they are made with will produce differing scales of texture. This is in keeping with the classical friction theories and literature relating to the interaction between rubber and imperfect surfaces. Microtexture is important at all typical speeds experienced for a road but is considered to be more prevalent in the tyre/surface interaction at lower speeds. Macrotexture becomes increasingly important at higher speeds in order to dissipate water in wet conditions.

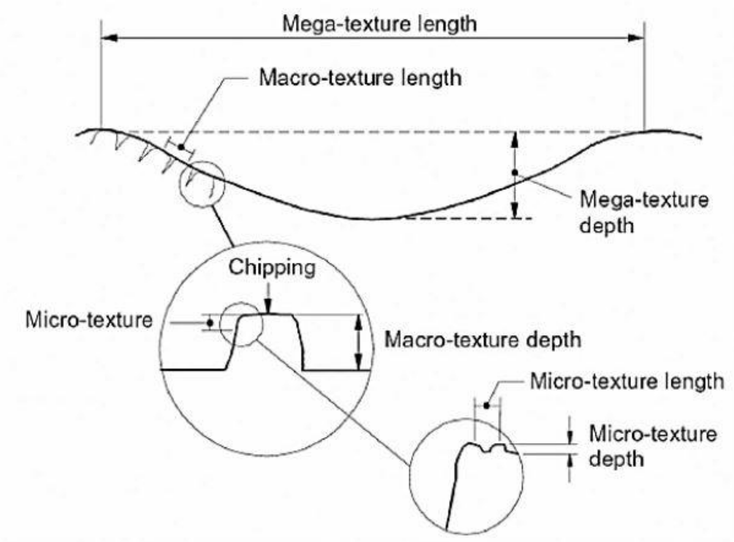


Figure 2-6- Diagram of Texture Length and Depths (DRMB, 2015)

The influence of texture wavelength on the tyre/surface interaction is shown in Figure 2-7. This illustrates the wavelengths at which different components of the tyre/surface relationship become prominent and the friction mechanisms that are associated. The three main textures are defined as:

- Microtexture is the microscopic roughness of the aggregate/fine aggregate particles or asperities.
- Macrotexture is the gaps between the aggregates and surface bed or voids of grooves in a grooved surface.

- Megatexture is the variation of the surface as a whole on a larger scale and includes ruts, potholes or cracks which are capable of causing disruption of the tyre walls but not the suspension.

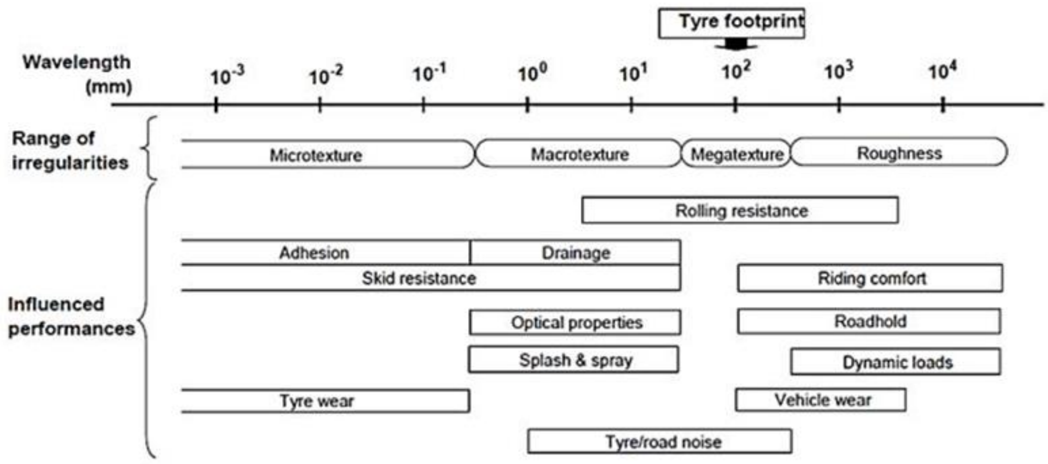


Figure 2-7 – Influence of texture wavelengths on tyre/surface interface (Kane et al., 2009)

The interaction of a road surface with a tyre has been defined as the result of adhesion and bulk hysteresis loss (Kummer (1966), Hall et al., (2009), Millar (2013). Adhesion is the frictional contact force resulting from the interaction of the tyre with the microtexture whereby the asperities are bonding, breaking, deforming and reforming at the point of contact. It is important for the adhesion component to have good contact to be effective i.e. free from contamination or lubrication.

The bulk hysteresis loss is the loss of energy from the deformation of the tyre surface as it interacts with the macrotexture (Hall et al., 2009). The hysteresis component requires the cyclic deformation of the rubber and a rough surface (Kane et al., 2009). The major component experienced at high speeds has been shown to be hysteresis compared with relatively low speeds when adhesion is considered to be the predominate friction component (Kummer, 1996), (Dewey et al., 2002).

Smith (2008) determined that Savkoor's (1965) adhesion in rubber theory is principally a result of Van der Waal's forces. This acknowledges that the previous assertions from Bartenev and Lavrentjev (1961) as true highlighting that when the interacting surface is of a rough texture, asperity interlocking is present at the same time as bulk deformation hysteresis. Therefore, if Van der Waal's adhesion is also in action then the three mechanisms work together. Kane et al. (2009) attains that Van der Waal's molecular adhesion mechanism can only work if the distance between the rubber and surface is less than 10^{-6} mm in other words on a clean, dry surface.

Woodward et al,. (2005) states that the tyre/surface interface is the point at which all the vehicle dynamics are transferred through to the surface including all associated stressing such as acceleration, braking, cornering and speed. Grip at the point of contact is complex and is related to a wide range of characteristics including those of the tyre, the surface material and environmental factors at the time of contact (Kanafi, 2017). The following parameters of a surface material will effect surface texture, skid resistance and overall friction or grip (Kane et al., 2009), (Dahir et al. 1978) (Folliard et al. (2002):

1. Aggregates – shape, size and type.
2. Bitumen – content and type.
3. Void content.
4. Paving and compaction of asphalt surface.
5. Texturing of surfaces – such as brushing, grooving, exposed aggregate including high-pressure water retexturing.
6. Asphalt/concrete – the types of surfacing.

Mineralogy is key to understanding aggregate properties such as wear and grip. Levels of wet grip can be classified according to rock type. Greywackes and sandstones tend to have highest wet grip, followed by granites and basalt. Limestone typically has the lowest wet grip (Woodward et al., 2012). The property of aggregate wet grip is measured using the Polished Stone Value (PSV) (BS EN 1097-8:2009) and the Friction After Polishing (FAP) (BS EN 12697-49:2014) test methods. Specifications for road and runway surface materials have used these test methods for many years to select suitable aggregates. The strength of the aggregate is important for structural integrity of the surface, particularly its macrotexture.

Kane (2009) concludes that the microtexture on an aggregate of a surface is affected by three factors: polishing; differential wear and weathering. Polishing is defined as the abrasive softening and rounding of an aggregate reducing the microtexture. Do et al. (2009) observed that two polishing mechanisms are at play with one tending to remove materials or asperities from the aggregate microtexture and the other that can regenerate roughness due to the differing hardness between aggregate minerals.

The bitumen binder content of an asphalt surface mix can have a bearing on grip especially in the early life stages. A high binder content will provide a lower void content thereby reducing macrotexture. The use of a polymer modified bitumen (PMB) can be used to improve the tensile strength of the surface (Kane et al., 2009).

Construction practice can have long-lasting effects if the use of the paver and roller compaction are not satisfactory. Kane et al. (2009) suggests that temperature of the mix, segregation in the horizontal direction from poor use of the paver and over-compaction with the use of roller vibration can have a negative effect on macrotexture.

Environmental factors contribute to the measured grip available to a moving vehicle and may be local or seasonal. Typically, measured grip is lowest in the summer and increases in the winter through seasonal weathering and polishing cycles (DRMB, HD/28:2015).

2.6 Early life surface phases

An asphalt road surface will experience early life changes in grip and other texture related characteristics (Woodward et al., 2005; Roe et al., 2005; DRMB, HD/28:2015). There is a complicated set of inter-relationships between factors such as type of aggregate, bitumen composition, surface texture, time of year and site location when considering skid resistance. A new surface positive texture such as a hot rolled asphalt (HRA) or surface dressing will undergo an early exposure of the aggregate due to wearing of excess binder (Woodward et al. 2005).

Negatively textured surfaces such as stone mastic asphalt (SMA), porous asphalt and proprietary thin surface course systems will take longer to wear away any excess bitumen and expose the microtexture of the aggregate. The use of a polymer modified bitumen will extend the time taken for aggregate exposure.

A phenomenon known as bitu-planning can occur during the early life of a bitumen surfacing material. Roe et al. (2005) found new surfaces had about 20% less skid resistance at lower speeds and 30-40% less at higher speeds compared to mature surfaces where excess bitumen had been worn off. At low and medium speeds, dry friction was similar to wet friction. At very low speeds the high level of wet friction can exceed dry friction. They theorised that the time taken for the phenomenon to complete and the surface to reach equilibrium varied depending on the amount of trafficking and local conditions. With light trafficking it could take up to 18 months for a road surface to reach equilibrium.

Roe et al. (2005) observed that the early life phenomenon is caused by a thin film of bitumen, which can adhere to the aggregate for a significant time. This can be extended by the introduction of a PMB into the bitumen mix. This was found to have three effects. Firstly, blinding the microtexture of the aggregate and changing the tyre/surface interface dynamic which resulted in lower wet friction at high speeds than experienced on a mature surface. Secondly, it resulted in a different adhesive mechanism which provides high friction at low speeds despite the microtexture being obscured. This is at odds with conventional thinking of the adhesive component of friction of the tyre/surface interface. Thirdly, bitu-planning can occur as a dry skid resulting from softening of the bitumen due to the increased heat generated at the interface. This phenomenon can result in a decreased level of friction or grip when compared to a mature surface.

2.7 Wet and dry grip

Measurement and specification of grip in the context of roads and runways always relates to a wet condition (DRMB HD/28, 2015). A film of water acts as a lubricant. It interrupts the tyre/surface interface and formation of interlocking bonds disrupting the adhesion and bulk loss hysteresis friction components. A hydrodynamic pressure is created that increases with the square of the vehicle speed (Kane et al., 2009).

Gough (1974), conceptualised the Three-Lubrication-Zones concept of water displacement by a rolling sliding tyre. The model shown in Figure 2-8 considers that while a fraction of water is displaced by the passing tyre, the tyre generally travels on an unbroken water film as shown in Zone 1. The middle Zone 2 is transitional where some physical contact between the tyre and surface is experienced. Zone 3 illustrates the area where only a thin film of water is present. At this point, the tyre is in contact with the microtexture of the aggregate.

Smith (2008) concluded that the majority of skid resistance develops in Zone 3 and the relative size of the zones is dependent on the speed. If the speed becomes too high, hydroplaning can occur. The role of microtexture is important new and trafficked surfaces in order to create good contact between the surfaces when a wet film of water is present.

At high-speed water being displaced or squeezed out in Zone 2, under the tread of the tyre, may produce water spray. This will impact visibility for drivers in wet conditions which is dangerous in motorsport.

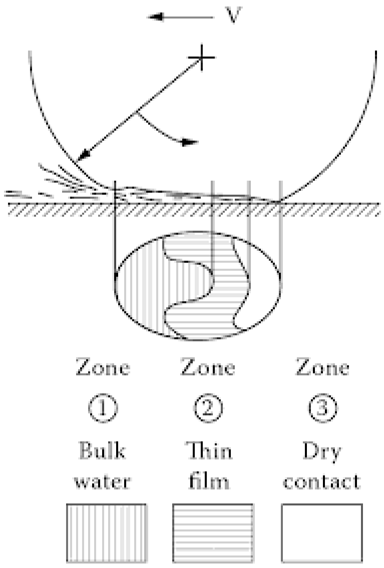


Figure 2-8 - Gough's Three-Lubrication-Zone Concept (Smith, 2008)

When the level of lubrication between a tyre and surface the vehicle will lose control in a phenomena known as aquaplaning. The effectiveness of the adhesion component is compromised as the surface macrotexture becomes unable to drain the water creating a surface water film. The tyre/surface interface is comprised resulting in a loss of vehicle control (Barbara etal., 1970).

2.8 Methods of measuring grip

In Europe, there are over 22 different CFME devices used to measure grip. Seventy nine percent (79%) of European countries measure grip of motorways and primary roads. Do and Roe (2008) reviewed each device and the countries where they are used. A number of European projects have attempted to harmonise CFME devices including HERMES, TYROSAFE and ROSANNE.

The devices can be grouped broadly into three categories: longitudinal friction, transverse friction and static friction techniques. The pendulum tester is an example of a static technique, the Sideways-force Coefficient Routine Investigation Machine (SCRIM®) is an example of the transverse friction measurement technique due to the placement of the measuring tyre at an angle to the direction of travel. The

GripTester is an example of a longitudinal friction tester as it uses a straight-line, fixed slip measuring principle to simulate the action of a braked wheel (Do and Roe, 2008).

2.8.1 Static skid resistance devices

Static friction devices are used to carry out spot tests either in the laboratory or on site. The main methods are the British Pendulum Tester (BPT) (BS 7976-2:2002) and the Dynamic Friction Tester (DFT) (ASTM E3145 – 18, 2018). Both devices rely on the principle of measuring the loss of kinetic energy as a rubber slider moves over the test surface. As the kinetic energy is dissipated it is transferred to a frictional force and therefore the available skid resistance from that given surface (Saito et al., 1996).

2.8.2 Transverse skid resistance devices

The transverse CFME testing methodology measures a side force friction by pulling a standardised measuring wheel along the surface at an angle. For example, the Mu-Meter which is primarily used on airports has two freely rotating test wheels at an angle of 7.5 degrees to the direction of travel (ASTM E2666-09, 2014). This is pulled along a wetted surface with the test wheels held under a static load. Measurements are normally taken at the speed of 65 Km/h (Lu et al., 2006).

The test tyre of the SCRIM® is angled at 20 degrees to the direction of travel (BS 7941-1:2006). The side-force coefficient (SFC) is defined as:

$$SFC\ (V, \propto) = 100\ x\ (\frac{Fs}{W}) \qquad - (6)$$

Where: V is the velocity of the test tyre, α is the yaw angle, Fs is the perpendicular force and W is the vertical load applied to the measuring wheel.

2.8.3 Longitudinal skid resistance devices

The longitudinal CFME devices can be classified into two main testing methods: braked wheel devices and locked wheel devices. Locked-wheel friction devices are designed to simulate a locked wheel on a road surface in conditions similar to emergency braking. An example of this would be the Locked-wheel Skid Trailer (ASTM E274/E274M – 15, 2015). The device is normally run at a higher speed, between 60 and 95 Km/h using a smooth tyre. A ribbed tyre is thought to be insensitive to the water film used, meaning that it does not measure macrotexture effectively (Hall et al. 2009). The measured data is reported as Friction Number (FN) or Skid Number (SN) depending on the manufacturer. The Friction Number is given by:

$$FN(V) = 100\mu = 100\ x\ (\frac{F}{W}) \qquad - (7)$$

Where: V is representative of the velocity of the measuring tyre, μ is the co-efficient of friction, F is the drag or traction force experienced by the tyre and W is the vertical load applied to the measuring tyre (ASTM E274/E274M – 15, 2015).

Fixed-slip devices such as GripTester MK2, micro GripTester, ASFT Runway Friction Tester and Via-Friction maintain a constant slip ratio of between 10% and 20% while applying a vertical load. This is thought to be more akin to the experience of a vehicle with anti-lock brakes (Henry, 2000). The frictional forces measured are described as being more sensitive to microtexture due to the small slip ratio employed. The measuring tyre rolls in the longitudinal direction of travel and the slip can be calculated as:

$$Percentage\ Slip = \frac{(V - r\ x\ \omega)}{V}\ x\ 100 \qquad - (8)$$

Where: the Percentage Slip is the ratio of slip speed in comparison to the test speed, V is the test speed, r is the effective rolling tyre radius and ω is the angular velocity of the test tyre.

2.8.4 Macrotexture measurement

The Volumetric Patch Technique (BS EN 13036-1, 2010) or sand patch test as it is commonly referred to; is considered the reference method for measuring macrotexture on highways and airports. It is a simple method and involves pouring a known volume of standardised sand or glass beads onto the surface. This is then spread evenly to make a circle or patch of sand. The diameter of this circular patch is measured and used to express macrotexture as a Mean Texture Depth (MTD) in millimetres. It is thought that this patch is representative in size of the contact patch of a vehicle tyre (DRMB HD/28, 2015). The MTD is calculated from:

$$MTD = 4V/\pi D^2 \qquad - (9)$$

Where: V is the sample volume and D is the mean diameter of the patch.

Millar (2013) concluded that this method of quantifying macrotexture represents surface texture in only one dimension which is of limited use to researchers interested in the tyre/surface interaction. Mean Profile Depth (MPD) was developed as an alternative to MTD to measure the profile curve of a surface using a laser mounted on a moving vehicle. This has subsequently evolved into measuring macrotexture using a wide range of 2D and 3D parameters that are more representative of the surface compared to a circular patch of sand.

2D and 3D measurement systems are now used to measure all texture scales. This can be carried out as either spot tests or at high-speed using static or dynamic devices. For example, the Surface Condition Assessments of National Network of Roads device (SCANNER) (Pavement Condition Information Systems, 2009) uses lasers and high definition video cameras to measure texture at high speed (DRMB

HD/28, 2015). Static laser devices are used to quantify the smaller texture scales either in 2D or 3D. Sangiorgi et al. (2012) showed how analysis of roughness using MPD and the Abbot-Firestone Curve (AFC) could be used to characterise surface properties.

A method using Close Range Photogrammetry (CRP) was developed by Millar (2013) to create detailed 3D surface texture models. This was further developed by McQuaid (2015) to investigate surfaces at microtexture scale. Compared to 2D and 3D laser based methods, the CRP method is simple, cost-efficient and quick.

2.9 Tyre Enveloping and how to measure it

The concept of enveloping is related to the bulk deformation of the vehicle tyre around the surface texture. As the tyre compresses, it deforms into the surface texture where energy is gathered in the tyre. When the tyre relaxes as it rotates losing contact, part of the energy is lost in the form of hysteresis/heat while the rest drives the tyre in the direction of travel (Hall et al., 2009). The tyre does not make contact with every part of the surface material as it moves over it. The tyre is said to be enveloping the surface material it makes contact with.

Enveloping was highlighted as an area for further work by the ROSANNE (2016) project (Goubert et al, 2014). Traditionally enveloping theory had played an important part in the prediction of tyre and road noise which is important for highways. Goubert et al. (2014) explored the different algorithms found in literature to estimate how the tyre deflects when in contact with a surface. Vieira et al. (2018) used the von Meier algorithm to illustrate enveloping on two different surface types. Figure 2-9 shows an example comparing two artificial macrotexture profiles. This shows different contact with a tyre leaving large sections of macrotexture not contacting the tyre at all.

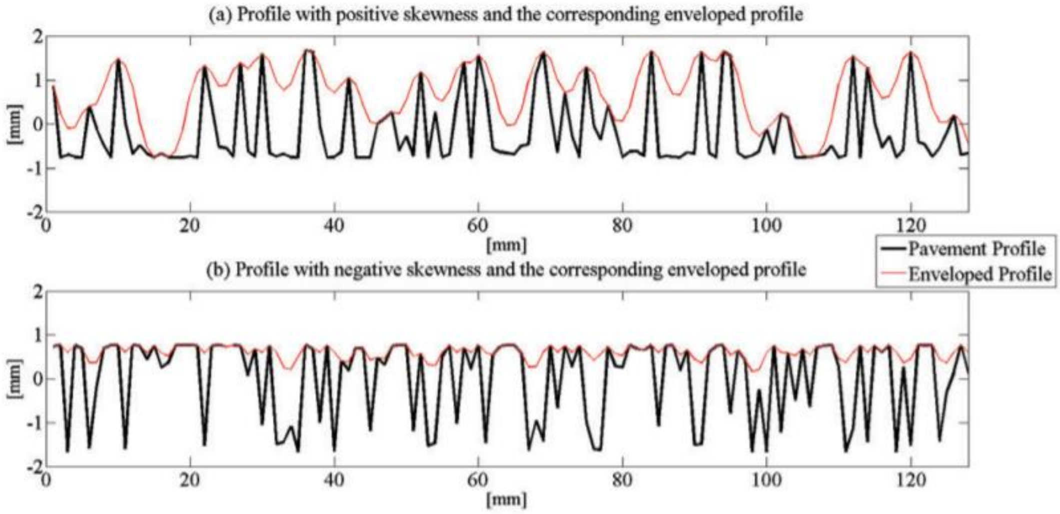


Figure 2-9 Artificially generated textures with a positive texture (a) and a negative texture (b) (Vieira et al., 2018)

Casey et al. (2018) demonstrated that 3D CRP offers a new way to gain a deeper understanding of tyre/road enveloping that is cost effective, quick and simple. This is of use in motorsport to better understand the tyre/surface interaction and how it relates to grip.

2.10 Motorsport Surfaces and Grip

Due to the secrecy in motorsport there is little literature relating to racetrack grip, specifications of racetrack surface grip, testing requirements or even what the teams know. There is currently no published FIA specification or recommendation for track surface materials or characteristics. Current FIA guidelines are focused on safety in areas such as barriers, runoff zones, antiskid paints/track markings, marshal posts, driver briefing requirements and corner designs. An FIA track grading system to determine suitability of race circuits to hold certain level of motorsport events exists but does not have track surface criteria (https://www.fia.com/circuit-safety).

A meeting at the Singapore Grand Prix 2017 with Charlie Whiting, FIA Formula One Race Director, confirmed that the FIA do not specify a minimum level of grip. This is due to the belief that all vehicles race on the same surface so it is the same for everyone. One hurdle is finding a compromise that meets the needs of the different motorsport stakeholders. The FIA require a safe, consistent track surface. Formula One would like a high grip surface that should cause high degradation of tyres and wear resulting in more pit stops which they believe increases the excitement of the racing.

The teams and tyre suppliers want a predictable grip surface that can be modelled to optimise tyre selection and minimise the need for excessive number of pit stops. Track operators require a hard wearing, low maintenance surface that will not cause amateur track users and track day operators who make up the core of their business to wear out expensive tyres prematurely.

In the future the FIA may look towards the homogenisation of racetrack surfaces once their current barrier and catch fence project is complete. This should ensure a consistent track surface with an appropriate level of grip and other surface characteristics are present for motorsport events.

Case studies have been written about the Circuit of Americas F1 circuit (COTA). Although these have focused on promoting plant and contractors there is some insight into the track surface properties. The COTA construction contract stated that the surface will undergo large levels of shear stress rather than downward stress normally associated with a highway pavement. Therefore, strict requirements for gradation of aggregate and high quality bitumen is required (Anon (a), 2013). No further details are recorded other than to emphasise the proprietary nature of the custom mix material and control requirements implemented.

An article reported on the use of asphalt plants in the construction of the COTA F1 circuit and profiled the supplier of the mixing plant equipment (Anon (b), 2013). Tom Byrum of Austin Commercial is quoted as saying:

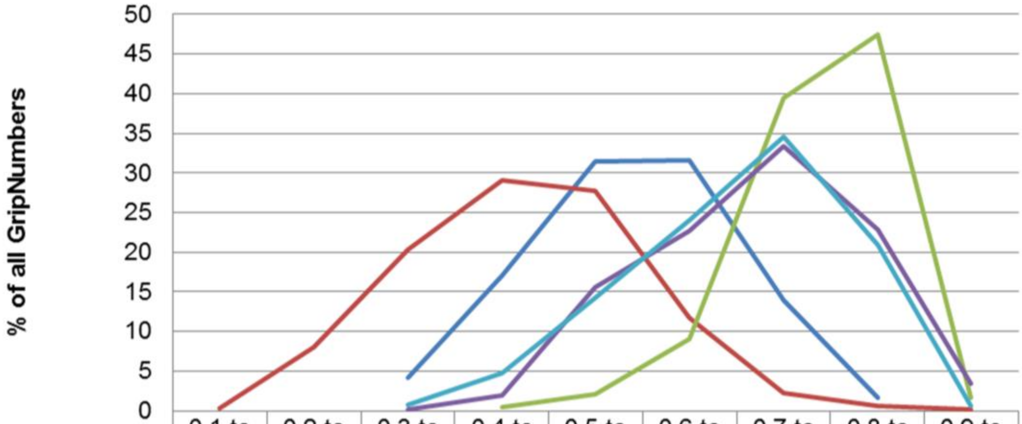
> ‘First, the surface mixture is a high-performance friction course with a high level of skid resistance, and the asphalt cement represents 6.5 per cent of the

> mix. At PG 82-22, the liquid asphalt was highly modified with SBS (styrene-butadiene-styrene) polymer. It could be considered a Superpave mix, very similar to stone-matrix asphalt, with high binder content and gap-graded aggregate, providing rock-on-rock contact with minimal fines. The track had to be durable and skid-resistant.'

This is similar to the surface specification used in Singapore for the F1 track issued as guidance for the tendered contract. The contract outlined the 'supply and lay of F1 SBS (Styrene Butadiene Styrene) PMB (Polymer Modified Binder) asphalt concrete' which is defined as being of high resistance to deformation, resistant to high shear forces high resistance to flexural cracking and high skid resistance.

There is little research written about the grip of racetrack surfaces. One of the few published papers on the measurement of racetrack grip variation is by Woodward, Millar and Waddell (2012). Until this paper was published, race tracks were known to have a defined racing line with some tracks considered to have more grip than others. This paper was the first to consider mapping grip in both the longitudinal and transverse directions to show how it varied for the entire width and length of the track.

Figure 2-10 illustrates one example of how the measured grip data can be compared for five different tracks as a frequency distribution. The different grip levels are clearly visible with Circuit C having higher grip compared to four other circuits.



	0.1 to 0.2	0.2 to 0.3	0.3 to 0.4	0.4 to 0.5	0.5 to 0.6	0.6 to 0.7	0.7 to 0.8	0.8 to 0.9	0.9 to 1.0
Circuit A			4.2	17.0	31.5	31.7	14.0	1.6	
Circuit B	0.3	8.0	20.3	29.0	27.8	11.7	2.2	0.5	0.2
Circuit C				0.4	2.1	9.1	39.4	47.5	1.6
Circuit D			0.1	1.9	15.6	22.7	33.4	22.9	3.4
Circuit E			0.7	4.8	14.3	24.1	34.5	20.9	0.6

Figure 2-10- Frequency distribution to compare circuit grip levels (Woodward et al, 2012)

2.11 How motorsport teams measure grip

The teams involved in the highest levels of motorsport are secretive of their data. There is no published literature or information on the techniques they use to measure grip. Figure 2-11 shows a staff member from Pirelli, F1’s tyre supplier, carrying out a surface scan of the track surface asphalt at COTA. The article which the photograph appears in contains no detail about the test other than that it is used to measure the track grip and aid tyre compound selection (Anon (a), 2013). The device pictured is thought to be a 2D laser scanner.

Figure 2-11 Pirelli representative taking a grip measurement at COTA F1 circuit (Anon (a), 2013)

Figure 2-12 Ames laser scanner used by an F1 team at the Singapore Grand Prix

At the 2017 and 2018 Singapore Grand Prix F1 events, several teams carried out laser scans of the track surface with a range of different devices. The scans were taken at three points through each corner; entry, apex and exit on the racing line as well as on the starting grid. The area scanned was selected by the operator. Figure 2-12 shows an Ames Laser Texture Scanner (LTS) Model 9400/9400HD being used on the Singapore Grand Prix track surface in 2017 by a member of an F1 team. It is not known how the data collected was processed or used.

Findlay Irvine's micro GripTester is now being used in two different motorsport categories by professional racing teams. This followed its first use at Singapore 2017 by this author. Two FIA Formula E race teams use a micro GripTester to evaluate wet grip before races. One FIA World Rally Cross (WRX) team use the same device to measure the grip level and any changes at the starting positions throughout the race weekend. It is not known how the data is used by the teams to affect the performance of their vehicles.

2.12 Critical Review

2.12.1 General friction and rubber friction theory review

Friction theory has been considered for hundreds of years. Early concepts and friction laws were established. The three laws of friction by Amontons (1669) and Coulomb (1773) have been accepted for many years. However, when the visco-elastic properties of rubber are considered, difficulties arise. Kummer (1966) proved that Coulomb's (1773) third law of friction is not applicable to friction caused by rubber hysteresis as it is not independent of the sliding velocity.

Researchers are in agreement that frictional properties that relate to rubber are complex and not fully understood. Various authors have compiled an informed guide to rubber friction but the complex range of variables do not yet allow for a universally agreed unifying theory. Authors cited in the literature review seem to agree on the main principles that comprise the mechanism of rubber friction as being adhesion and bulk hysteresis.

The literature suggests that the contact patch of a tyre on a highway surfacing is still not fully understood. There seems to be a general consensus that the adhesion component in the tyre/surface interaction is due to the molecules of the softer rubber being thermally energised which creates a stick/slip reaction. During this interaction, the rubber molecule chains attempt to bond to the harder aggregate and the sliding effect results in the bonds deforming, stretching, breaking and then returning to normal which cause a thermal reaction. This is particularly relevant to motorsport in the dry as the construction of race vehicle tyres makes them thermally sensitive both in their operation and degradation. In wet conditions the available friction is reduced. It follows therefore that there will be less heat generated at the interface.

2.12.2 Pavement surface critical review

Multiple terms are used interchangeably when referring to the tyre/surface interface such as friction, grip and skid resistance. The literature suggests that the most common understanding is that the terms *friction* and *grip* refer to the overall forces generated at the tyre/surface interface. These are attributable to vehicle dynamics, environmental factors and the tyre/surface contact. Skid resistance is the contribution of the tyre/surface contact only and is measured by a standardised test. To avoid confusion, these definitions are adopted throughout this thesis.

There is little published research into the effect of race tyres on track surfaces. However, a significant amount of research has been carried out regarding vehicle tyres and their interactions with roads. Although the forces generated, rubber compounds, rubber constructions and vehicle dynamics are different, the over-riding mechanisms involved in the interaction between a tyre and pavement surface are similar.

The limited literature available has shown most racetrack surfaces to be of a similar construction to road surfaces utilising either asphalt concrete (AC) or stone mastic asphalt (SMA) mixes with nominal 10mm aggregate, typically using a polymer modified bitumen.

With regard to the directional friction forces there is general agreement with the components that contribute to tyre/surface interaction. The forces are described as the longitudinal and lateral frictional forces. Both are important when considering grip. The longitudinal friction forces are important in respect of the methods presented in this thesis for measuring grip.

The lateral forces experienced by vehicles in motorsport play an important role in tyre management from generating the required heat, to degradation and tyre graining according to anecdotal observations by motorsport commentators.

A summary of the factors influencing road surface friction was compiled by Wallman et al (2001). Table 1 lists the main influencers in the complex interaction. Table 1, although useful, negates vehicle dynamics such as the effects of suspension, dampers, driver assisted aids and others instead grouping it all into load. This simplifies the model but restricts its usefulness when considering racing vehicles.

2.12.3 Racetrack Surface Characteristics

Pavement surface texture has three scales i.e. megatexture, macrotexture and microtexture. The influence of different textures and the importance of texture type with the tyre/surface interface components is still not fully understood. The general hypotheses in the literature agree that adhesion is the frictional contact force resultant from the interaction of the tyre with the microtexture. The asperities in this interaction are bonding, breaking, deforming and reforming at the point of contact. This is generally theorised as the component that most influences the tyre/surface interaction at low speeds and when lubrication is present.

Bulk hysteresis loss is observed as the loss of energy from deformation of the tyre surface as it interacts with the macrotexture. This is also considered to be the component of friction that has the biggest influence at high-speed. However, this has been questioned by researchers such as Yurong et al. (2004) who postulated that macrotexture in the form of inter-aggregate spaces may hold more importance on the friction/grip relationship at low speeds than has been initially thought.

Grip is highly dependent on the surface characteristics and materials. Extensive literature exists considering the surface characteristics and effect of materials in highway and runway pavements. Six main factors have been highlighted;. aggregates, bitumen, void content, paving/compaction, texture and type of material.

Consideration of the importance of aggregate quality dates back to the late 1800s. Three factors; polishing, differential wear and environment impact microtexture and the grip of a tyre. The geological hardness of the aggregate and the chemical composition determine its response to these factors. In motorsport a racing line is often referred to as being rubbered-in as it is trafficked. The racing line for a given track may be different to that of another and relates to whether it is being used by cars or bikes. Instead of a line, a track has a racing corridor across and along which grip and other surface characteristics vary continuously. Available literature does not adequately consider the reasons for such changes.

The construction methods used at the time of laying a new surface will affect the racetrack surface characteristics. Poor construction techniques will result in an unsatisfactory surface finish. It may not meet the requirements for macrotexture, evenness or drainage creating problems in wet conditions. Environmental seasonal variation and local climate factors can affect grip. This is important as motorsport events are held throughout the world in many different climates and in some cases an event may be cancelled should track conditions be considered unsafe.

The choice of bitumen is important. For example, polymer-modified bitumen will take longer to be removed from the surface than non-modified bitumen. This is important for the evolution of the racing line/corridor especially where part of a track surface may have been replaced prior to a major event. Negatively textured surfaces such as SMA have been shown to display lower early life grip due to potential bitu-planing.

The difference between grip in wet or dry conditions is acknowledged in the literature. The three-lubrication-zone model for wet conditions is frequently cited. A significant difference between many of the acknowledged theories and models relating to friction and its measurement on roads and runways is that the in-service measurement is always carried out under wet conditions unless specifically stated that testing was carried out in dry conditions.

2.12.4 Methods of testing grip

There are three main types of method used to test grip; static devices, transverse devices and longitudinal devices. They each measure slightly different components of the friction mechanism. Three devices have been reported in literature to measure race track grip; the pendulum tester, the GripTester MK2 and the micro GripTester. The pendulum is a spot test of a very small part of the tack surface. The GripTester and micro GripTester devices give a continuous measurement and allow generation of large datasets for analysis and evaluation.

2.12.5 Motorsport track surfaces and grip

There is little specific literature about motorsport surfaces and grip. Woodward et al., (2012) reported a mapping system which measures grip and allows quantifiable comparison of different race tracks. Discussions with motorsport industry leaders and regulators has shown a need for a better understanding of the contribution of racetrack surfaces to grip. This demonstrates the need to improve what is known in terms of grip from safety, maintenance and performance perspectives.

There is limited literature regarding the surface materials used on racetracks or the testing methods employed to ensure quality. This is partly due to the proprietary nature and commercially sensitive materials used. The limited information typically specifies a PMB and high PSV aggregate. A few examples of testing methodologies used by teams in motorsport have been identified. How the data is used is unknown.

2.13 Knowledge gaps

Based on the critical literature review the following knowledge gaps have been identified:

- There is little literature on the grip of surfacing materials used on racetracks.
- There is no established method of mapping racetrack grip.
- There is a need to show the spatial variation of grip around a racetrack in a way that can be visualised and the data included in other analytical methods.
- The new surface of a racetrack will develop a racing line corridor that will start to evolve once it is trafficked. The literature review has failed to find studies that consider this evolution.
- There is the need for a standardised method that can be made available to the motorsport industry that allows racetrack surface characteristics such as grip to be measured.
- There is a need for racetrack surface characteristics data to be made available for improving the current computer simulations and simulator models.
- There is a need for a decision matrix of potential grip measurement devices for use on racetracks.

CHAPTER 3

METHODS AND EQUIPMENT FOR DATA CAPTURE

3 Chapter 3 Methods and Equipment for Data Capture

3.1 Introduction

This chapter reviews the methods selected to measure the race track surface characteristics. The GripTester and micro GripTester were chosen to measure grip. The Volumetric Patch Technique and CRP 3D modelling were chosen to investigate macrotexture scale parameters.

3.2 Equipment considered to measure grip

A decision matrix is shown in Table 2 listing the skid resistance test devices against a range of desired criteria identified for testing racetracks. Each device is operated according to its standard. Consideration must be made to the test conditions at the time of testing when analysing the data from each device. The standard rubber used in each device and how it interfaces with different surface material types will influence the data. Interface conditions for the device will not be representative of the rubber compounds used in motor sport.

Table 2 Grip Measurement Equipment Decision Making Matrix

	CFME	Easy to Transport	Slick Measuring Tyre	Relevance to Motorsport	History Testing Race Tracks	Live Data Output	Intigrated GPS	Ability to test entire circuit	Ability to measure corners	Manufacturer Support	High Speed
Pendulum		X		X	X					X	X
SCRIM	X					X	X	X		X	X
GripTester	X	X	X	X	X	X	X	X	X	X	X
Skiddometer BV11	X		X			X	X			X	X
SRM/RoadSTAR	X					X	X	X		X	X
SAAB Friction Tester/ASFT	X		X	X		X	X	X	X	X	X
TATRA Runway Tester	X		X					X			X
ROAR	X		X			X	X	X		X	X
ADHERA	X		X					X			X
Profilograph GE						X	X	X	X	X	X
Portable Friction Tester (PFT)	X	X	X					X	X	X	
Pavement Friction Tester (PFT)	X					X	X			X	X
IMAG	X							X	X		X
micro GripTester	X	X	X	X		X	X	X	X	X	

Four devices were short-listed to decide which were most suitable to measure race track grip; the Pendulum (BPT) testing device, SCRIM®, GripTester MK2 and micro GripTester.

The British Pendulum Tester (BS 7976-2-2002). (Figure 3-1) is used around the world in the laboratory and in situ to measure low speed friction of roads and runways. The pendulum has been used in motorsport. It uses a swinging arm and rubber pad to measure the frictional properties of the test surface through the loss of kinetic energy as the arm swings and the rubber pad as it makes contact with the surface under test (BS 7976-2-2002).

Ciaravola et al. (2017) modified a pendulum to allow tribological tests on rubber tyre specimens. This is known as British Pendulum Evo. By applying estensimetric load cells which can measure tangential and normal contact forces from the rubber/surface interaction, the British Pendulum Evo allows evaluation under different conditions such as sliding speed and temperature.

The standard pendulum gives a slow speed measurement at approximately 10 km/h and is considered to better measure micro rather than macrotexture. As a result, the tester does not correlate well with CFME utilising tyres that operate at higher speeds and influenced more with macro scales of texture. High speed CFME are devices that use test speeds up to 95 km/h. Woodward (2010) noted difficulties of using the pendulum to measure skid resistance of higher textured surfaces. The rubber slider may not contain enough flexibility to suitably deform around the test surface (Woodward et al., 2016).

With respect to measuring grip variation for the entire racetrack it was decided that it would be of limited use.

Figure 3-1 - British Pendulum Tester (Munro Instruments, 2019)

Sideways force devices such as SCRIM® or SKM are built around a heavy goods vehicle. It is the preferred method to test the main road network of Europe. The machine dates from research carried out in the 1930s when a sideways force was first used to investigate skid resistance. The current design dates from the 1960s. The UK sideways force device uses a freely rotating pneumatic, smooth tread Avon SCRIM® tyre (BS 7941-1:2006, 2006), placed onto the pavement surface at a 20° angle to the direction of travel with an a known vertical load applied. A controlled water deliver is placed in front of the test tyre. BS 7941-1:2006 outlines the standard test parameters for using SCRIM®.

Although there is some reference to a sideways force device being used to test racetracks its ability to generate consistent data in the confined space of a race circuit is unlikely due to its size. The tight geometry of some corners would make it difficult to maintain standard test conditions such as speed. Therefore, it was considered impractical to use such sideways force devices to measure racetrack grip effectively.

Figure 3-2 GripTester MK2

The GripTester (GT) was initially developed to measure airport runways and offshore helidecks. It was then used to measure roads. The GT MK2 is now used throughout the world and is recognised by ICAO, UKCAA and is an approved device in the UK DRMB specification for measuring road skid resistance in accordance with DRMB, HD/28 2015. The GripTester is a trailer-based CFME and uses the longitudinal friction measuring principles. The device consists of three wheels: two drive wheels and one measuring wheel. For every full revolution of the drive wheels, the measuring wheel is limited to 85% revolution through a chain and gear system. A 32 spoke gear on the drive axle and a 27 spoke gear on the measuring axle controls the measuring wheel forcing a 14.6% slip ratio. The measuring wheel is attached to an axle which contains strain gauges that measure the vertical and horizontal loads placed on it (BS 7941-2:2000). These forces generate a value representative of the interaction between the measuring wheel and surface known as GripNumber (GN) which is given by:

$$GN = \frac{Fd}{\varrho} \qquad - (10)$$

Where: Fd is the tractive drag force in Newtons and ϱ the load force in Newtons.

It can be towed at speeds of up to 130 km/h. The standard speed for roads is typically 50 km/h or 65 km/h and 90 km/h for runways (BS 7941-2:2000). The GripTester is towed behind a van or vehicle carrying a water tank. This is typically of 250, 500 or 1000 litre capacity. An automatic water delivery system is used to deliver a standard water film depth directly onto the measuring tyre to simulate a wet road surface.

A Global Positioning System receiver is used to geotag each measurement. A Hemisphere A101 10Hz differential GPS receiver with <1m accuracy is typically used. Roadbase software running on a standard laptop provides the operator with a real-time visual display of measured wet grip values. The software outputs the data in a csv format with each GripNumber data point matched to a speed, axle load, water flow, chainage, GPS latitude, longitude, altitude and time data.

The manufacturer of GripTester, Findlay Irvine Ltd, states that a tolerance of ±0.03GN for each machine and ±0.03GN for different measuring tyres is to be expected (Thomas, 2008). In 2009, a precision trial involving GripTester MK2 calculated a repeatability of 0.05GN and reproducibility of 0.12GN (Dunford, 2010).

The GripTester MK2 uses a standard smooth measuring tyre which is manufactured in accordance to ASTM E1844-08 (2015). The measuring tyre has a measuring tread width of 51mm. During testing a grip measurement is collected every 50 mm as the tyre rotates. These values are averaged and reported every 1 m. This equates to 19.6 data samples for every 1 m surveyed. The measuring tyre is liable to surface oxidation when not in use. Pre-running the equipment before carrying out a survey for around 2-5 kms to prepare the measuring tyre is recommended.

Compared to the other devices listed in Table 3 the GripTester offered most scope for use on race tracks. It gives a spatially referenced grip measurement every 1 m that is sensitive to the variations found on a race track. Being a trailer based device it can be put in the back of a van and driven to the track or it can be shipped overseas. The GripTester is the main device used in this thesis to measure grip data.

The Findlay Irvine micro GripTester, shown in Figure 3-3, is a CFME and was initially designed as a replacement for the British Pendulum. The micro GripTester utilises the same measuring principles as the larger GripTester MK2. It was designed to be used as a push device for areas where a GripTester MK2 cannot be towed. The unit has an integrated data capture and display device and automatic watering system.

The micro GripTester and GripTester MK2 are designed to produce the same reading under the same test conditions. In other words, if a GripTester MK2 is pushed at the same speed as a micro GripTester using the same water film depth, they will produce a 1:1 measured value (allowing for the manufacturers ±0.03 GN difference in machine and ±0.03 GN variance for different measuring tyres).

Figure 3-3 Findlay Irvine micro GripTester

The micro GripTester uses the same fixed slip principle as the GripTester MK2. The device uses the same slick standardised measuring tyre conforming to ASTM E1844-08 (2015) and treaded drive tyres utilised by the GripTester MK2. A proximity sensor is attached to the left drive tyre which counts passes of sixteen magnets housed in the wheel hub to produce a speed and distance measurement. This generates a grip measurement every 50 mm.

A touch screen display located at the top of the device handle allows variables such as test speed and distance to be controlled and programmed before commencement of the survey. Test speed can be set between 0.1m/s and 1m/s with 0.7m/s recommended by the manufacturer.

The software controls a water delivery system on the device handle to place a user-defined amount of water directly onto the measuring wheel. The software allows for a water film depth of 0mm, 0.25mm, 0.5mm or 1mm. A GPS receiver is positioned on the centre of the machine under the cover, 400mm behind the measuring tyre. The accuracy of the GPS receiver is <10m using operating at 1Hz.

The micro GripTester is prone to similar limitations as the GripTester MK2 due to the similar measuring methodologies. These limitations are inherent in most commonly used CFME. The micro GripTester is a pushed device and therefore is subject to potential variations in results caused by the operator. The measuring tyre must be prepared before a survey. The Findlay Irvine User manual states that the measure tyre should be scrubbed with an abrasive brush or steel wool before commencement of any survey.

The micro GripTester is particularly sensitive to microtexture rather than macrotexture (Zuniga-Garcia et al., 2016). The size of the micro GripTester makes it portable, quick to use and simple to gather grip data. Since its first use at the Singapore F1 event in 2017, it is now being used to measure grip variation by teams in Formula E and WRX.

3.3 Measurement of race track texture

The simplest way to measure the texture of a track surface is the Volumetric Patch Technique (BS EN 13036-1:2010). Figure 3-4 shows the test being undertaken on the Singapore Grand Prix Circuit. It is influenced by operator interpretation and environmental conditions such as high humidity or damp surfaces. Testing cannot be done if the surface is wet. Although it can show differences in texture between parts of the track, the main weakness of the technique is that it tells little about the tyre surface interface.

Figure 3-4 Volumetric (Sand) Patch Test

Static laser scanner systems allow 2D and 3D surface texture parameters to be determined for a surface. Figure 2-12 shows an Ames LTS 9400 being used by an F1 team member on the Singapore Grand Prix track. This can calculate Mean Profile Depth (MPD), Texture Profile Index (TPI), Estimated Texture Depth (ETD), Root Mean Squared (RMS), Ra, Rq, Skewness, Kurtosis and VAR. This is done over a scanning area of 107.95mm x 72.01mm (Amesengineering.com, 2019)

The Ames LTS displays immediate results onto the inbuilt LCD screen. The device features an on-board GPS receiver allowing data to be utilised using spatial software. Data can be exported in CSV format for import into other analysis software tools. Data is stored in a binary .LTS file which can be analysed using proprietary Ames 3D viewing software. Figure 3-5 shows an example scan of a pavement surface using an Ames LTS9400HD.

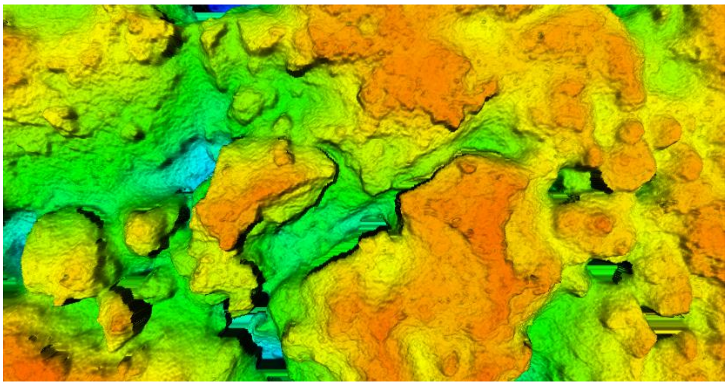


Figure 3-5 Ames LTS9400HD example texture scan (www.amesengineering.com)

The device is capable of producing these 3D scans by making multiple passes across the surface area and compiling the 2D profile scans. In a comparison of laser macro texture systems, Halil et al., (2008) found that a 2D profile potentially underestimates the actual texture. This was a problem with porous, open-graded and highly textured surfaces.

The ease of use for devices such as the Ames and ability to obtain data quickly is of benefit if simple 2D scans or only MTD is required. This makes it of interest to potentially time sensitive motorsport teams. The portable nature of the LTS is also beneficial. However, it takes much longer to complete multiple 2D scans than for 3D. The small scan size requires care when selecting relevant surface areas.

Optical 3D microscopes such as the Alicona PortableRL are now starting to be used to assess track surface texture. Figure 3-6 shows the Alicona device. It uses a non-contact, optical, 3D measurement principle based on Focus-Variation. The Focus-Variation technology combines the functionalities of a surface roughness measurement device and a form measurement instrument.

The Alicona PortableRL can measure fields of up to 62500mm^3 by utilising a large vertical scanning range that can measure various geometry types. It has a high measuring point density up to 500 million measurement points to achieve high vertical resolution. The digital microscope includes a battery pack which enhances its portability (Alicona, 2018).

Figure 3-6 Alicona PortableRL Digital Microscope (Alicona, 2018)

It is known that F1 teams now use digital microscopes including the Alicona models for research and development of their race vehicles. It can be used for platen inspection, quality assurance of parts, 3D measurement of steel and body parts. Promotional literature from Alicona shows their products are used by F1 teams on the track surface (Alicona, 2018). However, it is unknown who uses them or what the data is used for.

An alternative to laser scanning devices and optical microscope for measuring 3D race track parameters is based on the principles of Close Range Photogrammetry (CRP). A method using photographic images taken with a consumer grade camera was developed by Millar (2013) and further developed by McQuaid (2015) to investigate micro scales of texture. The method has been continually improved and is now known as the Ulster University Photogrammetric Method of Highway Surface Recovery and 3D Modelling (UUTex3D) (Millar and Woodward, 2019). Good results are now possible using smart phone photographs.

The method is simple to carry out. A marked straight edge is placed onto the area of surface to be modelled. Figure 3-7 shows the photographs for a CRP based 3D model being captured. A set of 12 to 15 images are taken working around the sample area. The photographs are then post processed in order to create a 3D model for surface texture parameter analysis.

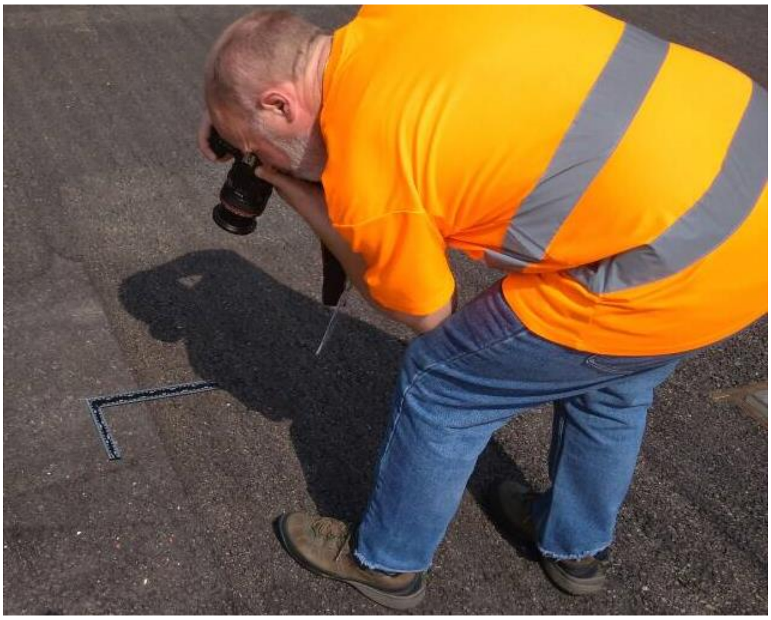


Figure 3-7 Taking photographs for a CRP 3D model

Figure 3-8 – Example of a 3D model derived from photographs

An example 3D model derived from photographs is shown Figure 3-8. Numerous 2D and 3D texture parameters can be determined from the models. Figure 3-9 shows an example showing how a 3D model can be used to estimate the depth of rubber enveloping. This example shows the area over which the rubber would envelope at a depth of 1.2 mm into the surface measured from its highest point.

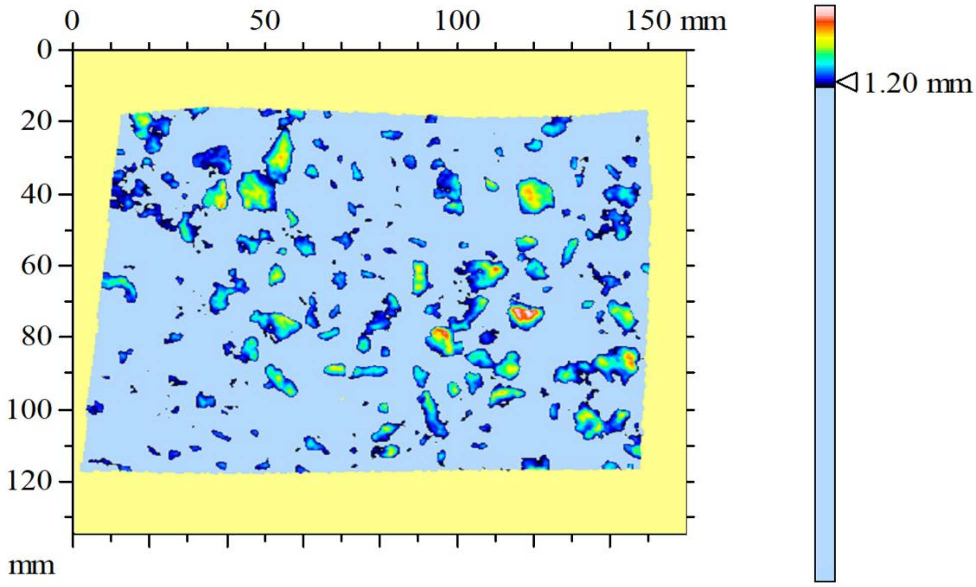


Figure 3-9 – 3D model illustrating tyre / surface interaction

The CRP technique based on photographs offers the ability to track variations as a surface evolves highlighting effects of material aging, material failing, tyre/surface interface, depth of tyre penetration, changes in micro and macro roughness, water dispersion and the effect of surface treatments. The process is limited to an area around 500mm x500mm for each 3D model. Therefore, care must be taken when selecting areas of interest to photograph in order to provide a representative sample of a larger area.

To ensure the accuracy of CRP models, the experience of the user is essential. Millar (2013) highlighted the need for accuracy of note taking when using CRP to sample an area. Experience of using CRP on racetracks has shown that the high volume of photographs required for each sampled area can become confused if not properly referenced.

Video systems are used in motorsport such as the Race Logic VBOX Video Data Logger shown as Figure 3-10. This synchronises high definition video footage with GPS to allow spatial analysis. Inputs can be integrated from the vehicle such as tyre surface temperature sensors.

Figure 3-10 Race Logic VBOX (www.vboxautomotive.co.uk)

The numerous types of data collected by motorsport vehicles have the potential to be used to indirectly measure grip and other track surface characteristics. It is not known exactly what motorsport teams measure. However, the onscreen media outputs shown during race events display real time vehicle data such as acceleration, braking, engine rpm and GPS positioning information. It is assumed that teams gather additional data such vehicle traction, yaw, steering action, tyre temperature, brake temperature or brake pressure which could be used to evaluate racetrack grip. However, it is impossible to get such data from motorsport teams due to the high level of secrecy within the industry.

Table 3 Requirements of motorsport stakeholders

Interested Party	Reasons for measuring grip	Current grip measurement technique used
Governing Bodies – FIA, FIM	• Improve safety • Homogenization of racetrack surfaces • Ensure high quality or appropriate surfaces for motor racing	None
Commercial Rights Holder – F1, DORNA	• Improved racing • Safe racing • Improved simulation data for the purposes of developing formula regulations	None
Racing Circuit Operators	• Consistent grip level for racing • Appropriate level of grip for motorsport and amateur users • Maintenance monitoring purposes • Predicting surface wear	Unknown
Tyre Supplier	• Development of tyre compounds • Aid tyre compound choices for individual races • Ensuring quality of tyre compounds by better simulation of tyre/surface interaction	• British Pendulum • 2D/3D laser texture
Motorsport Teams	• Improving Simulations • Improving driver performance • Improving racing performance • Improved vehicle set up • Predicting tyre wear/tyre selection • Reducing car setup work by improving vehicle performance	• British Pendulum • 2D/3D laser texture • micro GripTester • Vehicle dynamic data
Amateur Track Users	• Improving driver performance • Improving vehicle set up	• Unknown

3.4 Relevance of grip and other measurements to the motorsport industry

Table 3 outlines a summary of motorsport stakeholder requirements determined by interviews with motorsport professionals. The requirements were gathered from discussions with key personnel from FIA, F1, Petronas Mercedes AMG F1, Haas F1, McLaren F1, Techeetah Formula E, Williams Advanced Engineering, Prodrive, ADMM Yas Marina, Singapore Grand Prix and Knockhill Racing Circuit.

The interviews have identified that motorsport industry is interested in measuring racetrack grip and other track surface characteristics for a range of different reasons. Whether that be for the purposes of safety, improving on track performance, improved simulations or track maintenance, different stake holders have differing interests. Table 3 shows that there is currently no standard method available.

3.5 Chapter Summary

Chapter 3 has presented a review of the data collection methods that could be used to measure racetrack grip and other surface characteristics. This considered the most common methods used to measure grip in the highway and airport industries. This chapter has shown that knowledge accumulated in over seventy years of measuring highways and airports can be transferred to race tracks. The different requirements from motorsport stakeholders have been reviewed using information provided by key industry figures and organisations. This has identified the need to develop a standard method to measure racetrack grip that meets the diverse needs of these stakeholders.

CHAPTER 4

THE GRIPMAP METHOD

4 Chapter 4: The GripMap Method

4.1 Introduction

This chapter considers how to measure a race track for grip variation using a GripTester. This has been called the GripMap Method (GMM). The early development of GMM was summarised by Woodward, Millar and Waddell (2012).

This summarised their first use of a GT to measure UK racetrack grip in November 2007. Figure 4-1 plots GripTester data for 10 laps of the racing line for a racetrack in England. This found considerable variation around the track with respect to its wet grip with GN ranging from 0.23 to 1.07. Such variation in wet grip over such a small area would not be expected for a road or runway surface where a wet grip value of 0.42GN and 0.55GN respectively are the minimum acceptable grip levels.

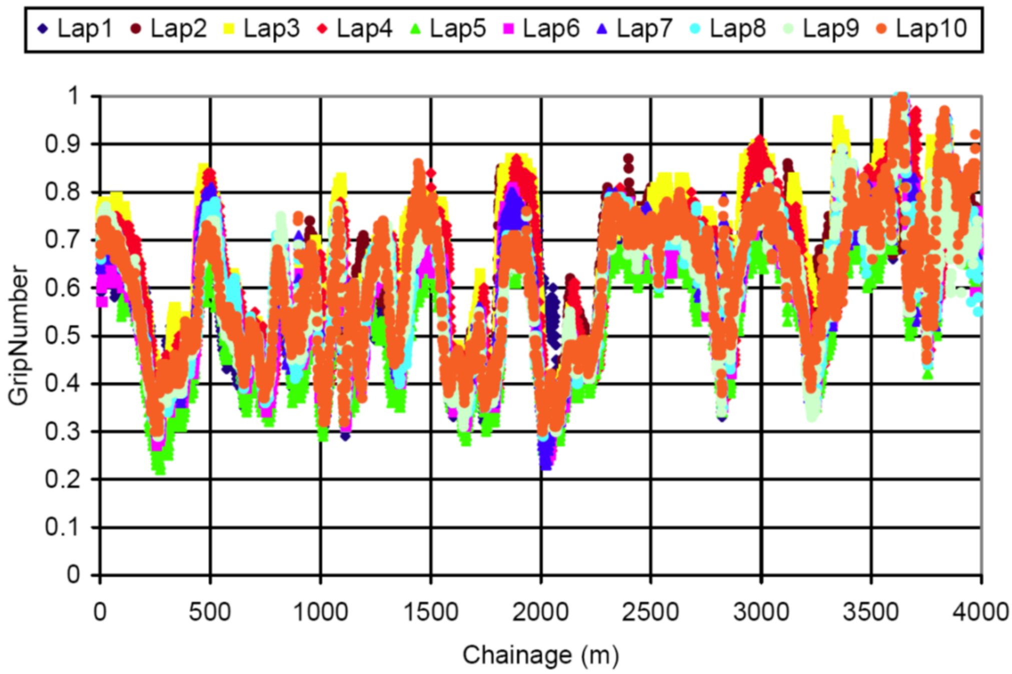


Figure 4-1 First GT data measured at a UK track (Woodward, Millar, Waddell, 2012)

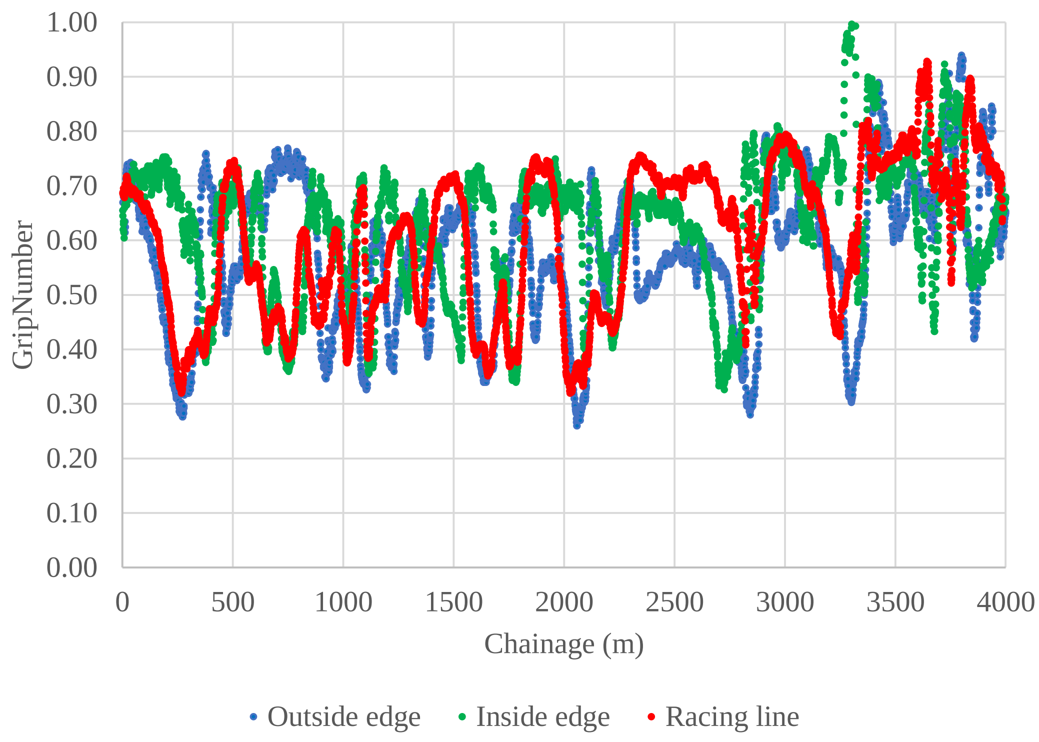


Figure 4-2 Comparison of grip measured in the racing line with the inside and outside edges

This suggested much greater variation in wet grip was present at a racetrack than for a road and that it was attributable to track use. Figure 4-2 plots data from this 2007 testing that compares racing line grip with data measured along the inside and outside edges of the track. There are significant portions of the track where wet grip is different to the racing line.

This suggested that lateral position on the track was important and related to track position within the racing line. Subsequent testing included the first use of a GPS to log latitude and longitude data during grip measurement at a rate of 1 Hz.

Figure 4-3 shows one of the first GripMaps showing both longitudinal and lateral variation based on GPS co-ordinates. This was plotted in Excel and clearly shows a racing line and lower wet grip associated with braking and cornering.

This Chapter considers how this early work was subsequently developed to investigate the main factors involved that has led to the standardised GripMap Method (GMM).

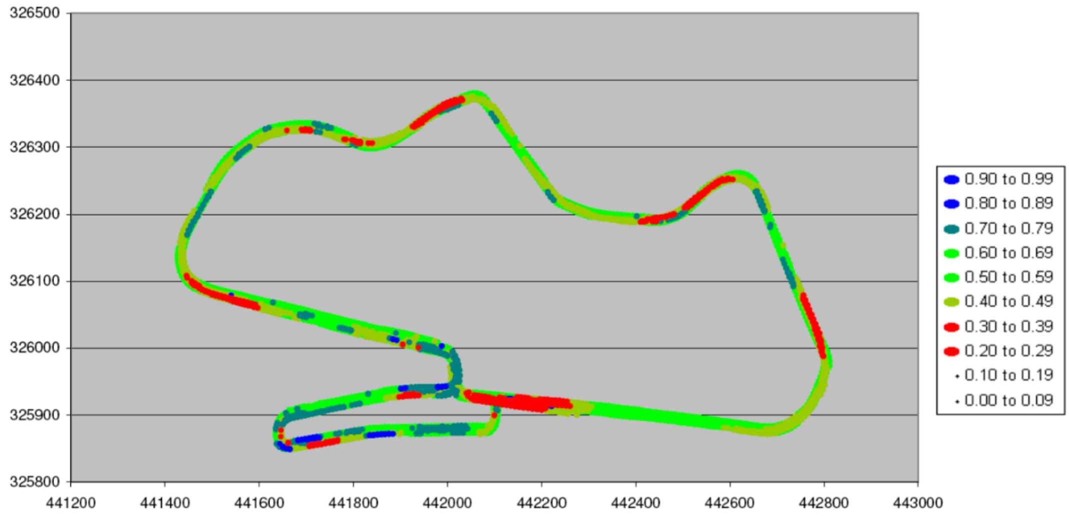


Figure 4-3 One of the first GripMaps plotted using Excel (Woodward, Millar and Waddell, 2012)

4.2 Standardising the GripMap Method test conditions

Based on experience from the road and runway measurement of grip, the main factors expected to influence GMM were test speed and water application rate to provide a water film thickness under the test tyre. Table 4 shows the standard GripTester survey speeds with the waterflow rate required to produce different levels of nominal water film thickness at the tyre/surface interface.

The standard test conditions for roads comprise of a speed of 50 km/h (±5 km/h) and a 0.25mm water film thickness. The standard ICAO test conditions for runway grip tests comprise of speeds of either 65 km/h (±5 km/h) or 95 km/h (±5 km/h) with a 1mm water film thickness (BS 7941-2:2000).

Table 4 Standard GripTester survey speeds and theoretical water film depth (BS 7941-2:2000)

Survey speed (km/h)	Theoretical water film thickness (mm)				
	0.20	0.25	0.30	0.50	1.00
6	1.0 l/m	1.2 l/m	1.5 l/m	2.5 l/m	5.0 l/m
20	3.3 l/m	4.2 l/m	5.0 l/m	8.3 l/m	16.7 l/m
50	8.3 l/m	10.4 l/m	12.5 l/m	20.8 l/m	41.7 l/m
65	10.8 l/m	13.5 l/m	16.3 l/m	27.1 l/m	54.2 l/m
95	15.8 l/m	19.8 l/m	23.8 l/m	39.6 l/m	79.2 l/m

The testing of road and runways involves either measurement in straight lines or round corners designed for the safe passage of vehicles. Due to the diverse nature of race circuits it was important to determine a suitable test speed at which a constant speed could be maintained without change. This would remove issues with how grip changes with speed.

Woodward, Millar and Waddell (2012) had found that maintaining the standard road-testing speed of 50 ±5 km/h. It was not possible to maintain a consistent speed at race track locations such as hairpins and chicanes. They proposed that a test speed of 30 km/h ±3 km/h was the optimum speed.

Testing was subsequently undertaken at Knockhill Racing Circuit to confirm that 30 km/h was the optimum speed. Two sets of tests were completed 6th August 2015 and 14th August 2015. GripTester GT534 was used with the same measuring tyre, serial number A70-150701, to ensure consistency. The weather was similar for both surveys. The track was observed to be damp from overnight rain but with no standing water and an ambient temperature of 11°C and 13°C respectively. All the tests were carried out on the racing line.

Three laps were attempted at constant speeds of 30 km/h, 50 km/h and 80 km/h. The speed data recorded by the GripTester MK2 is shown in Figure 4-4. In order to allow for a fair comparison, a validation margin of error of ±5% of the target speed should be achieved.

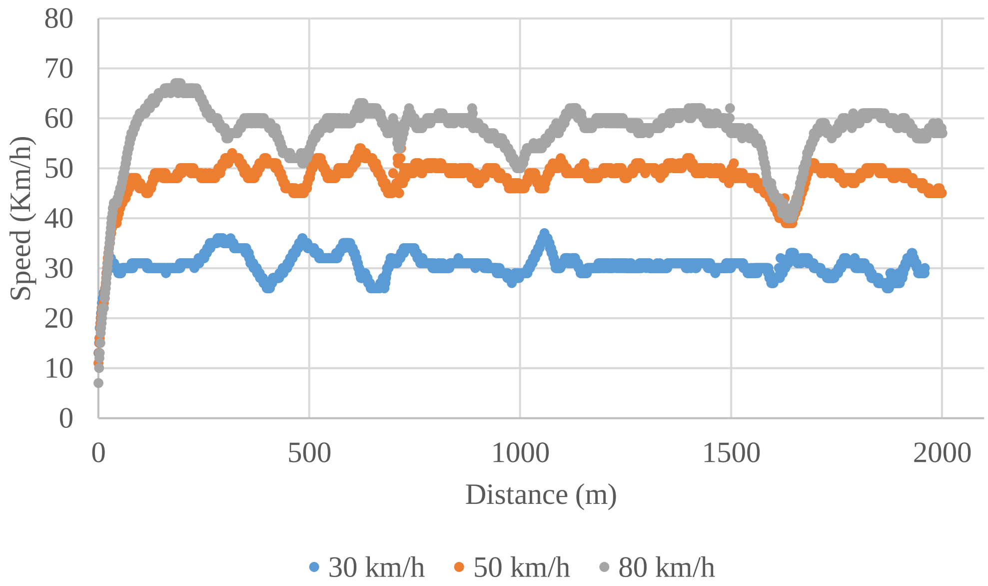


Figure 4-4 Racing line speed testing recorded 6 Aug 2015

An average speed of 30.6 km/h was achieved for the target speed test of 30 km/h. The target speed test of 50 km/h produced an average speed of 48.1 km/h. It was not possible to maintain a constant target speed of 80 km/h due to the capabilities of the VW Sharan tow vehicle. However, the recorded data for the attempted target of 80 km/h data falls into the ±5% margin for a target speed of 60 km/h.

At 1661m a dip in speed was recorded for the attempted 80 km/h test and a smaller drop at 50 km/h. This corresponds to the Hairpin corner at Knockhill which has a tight radius and steep incline. This speed testing at Knockhill confirms the findings of Woodward et al., (2012) that a constant test speed of 30 km/h is more achievable than the higher standard speeds used on roads or airports when undertaking grip tests on a racetrack.

Fluctuations in speed for all three test speeds correspond with the track geometry. The use of cruise control to reduce driver effects was investigated. Figure 4-5 demonstrates the improved consistency in vehicle speed when cruise control is used.

Deviations from the target speed still occurred at two areas around the circuit. The first is at a steep decline in track elevation known as Duffus Dip shown at distance 437m. The second is an incline at distance 579m approaching the Chicane. The sharp change in elevation caused the cruise control of the VW Sharan tow vehicle to disengage requiring the driver to compensate before re-engaging. This also occurred when the speed limiter function was used. It is recommended that grip is tested at 30 km/h using driver aids such as cruise control where possible.

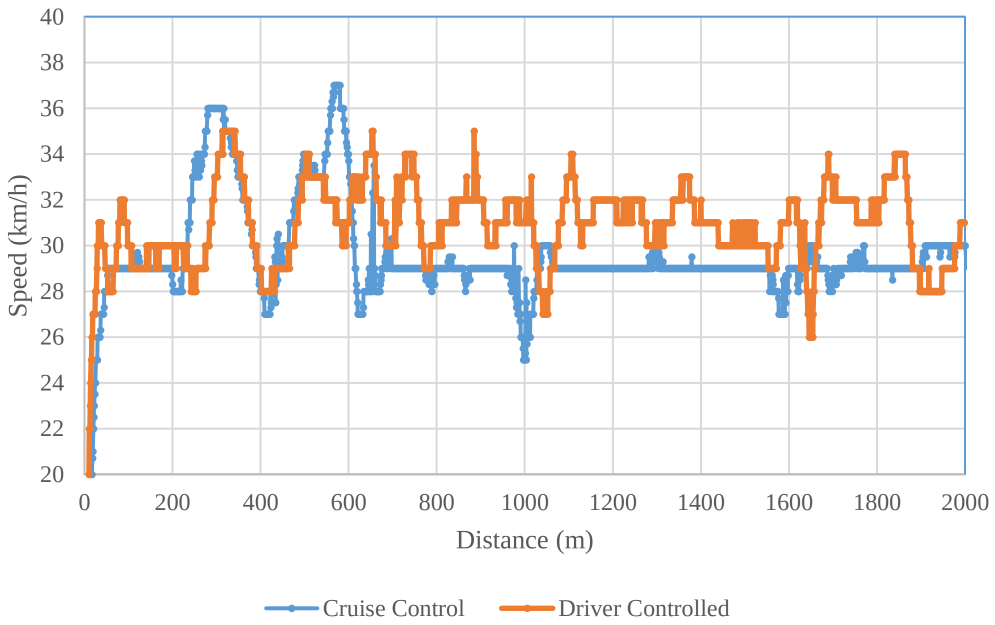


Figure 4-5 Driver aided speed control versus Driver operated throttle test

4.3 Effect of speed on wet grip measurements

Nursetiawan (2008) found that grip decreased as test speed increases on different road surface materials. This is shown in Figure 4-6. Where the influence of speed using a 0.25mm theoretical water film thickness was considered. Parallel linear trends were found for seven of the eight surface material types.

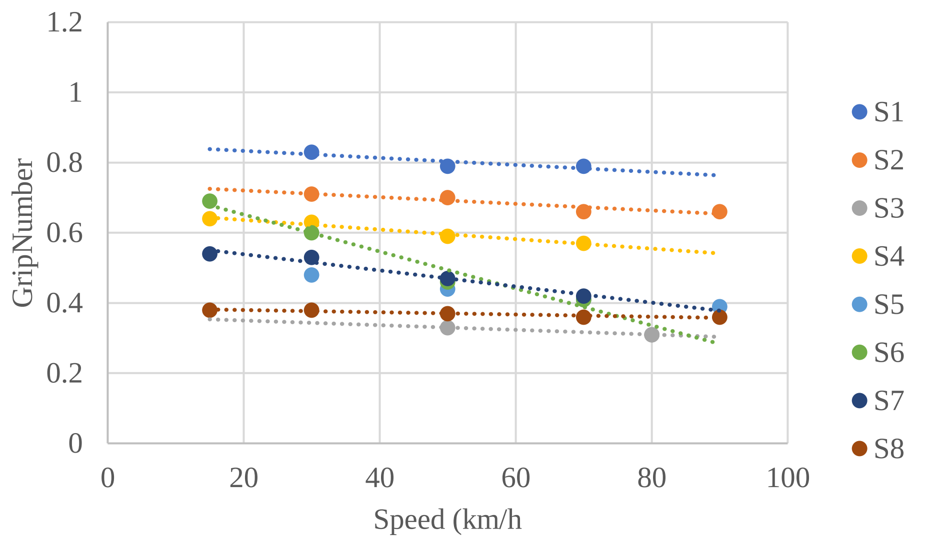


Figure 4-6 Effect of speed on grip levels with a water film thickness of 0.25mm (Nursetiawan, 2008)

The research by Nursetiawan (2008) on the effect of speed on wet grip was undertaken on straight sections of public highway. This experiment was replicated at Knockhill Racing Circuit to ascertain the impact of test speed on grip for a racetrack environment that included corners and undulations. Each speed test lap produced a similar sized data set measured at 1 m averages. The 30 km/h test produced 1962 data points, 50 km/h recorded 2002 data points and the 60 km/h captured 2004 data points. Figure 4-7 plots the measured wet grip values against the distance of one full lap of the circuit.

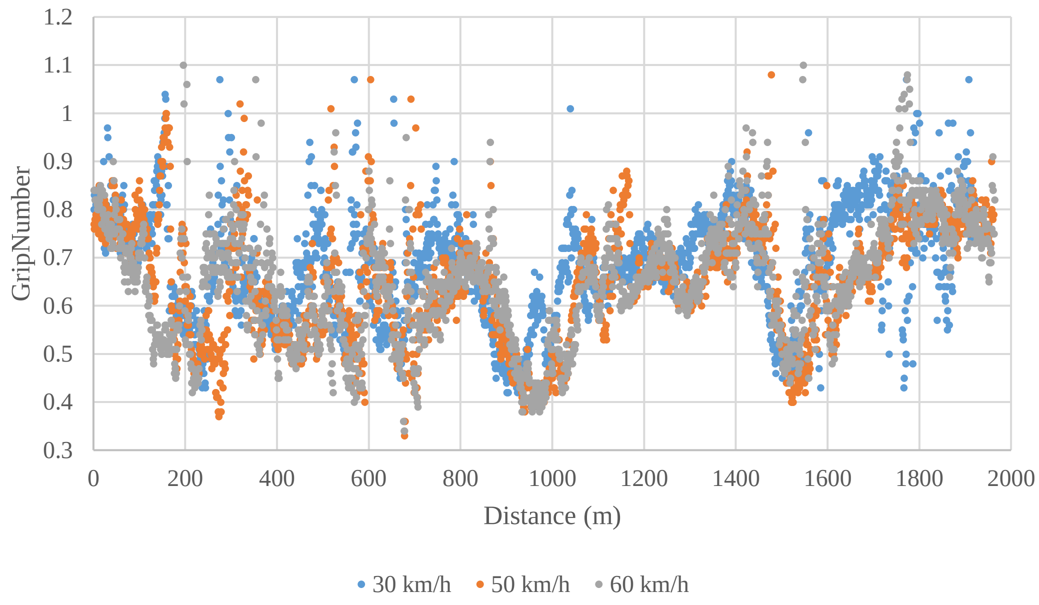


Figure 4-7 Effect of speed on measured grip

The plots show that all three speed tests follow a similar pattern. The grip values for the 30 km/h test are higher than those of the 50 km/h and 60 km/h tests. The mean of the 30 km/h test is 0.71GN, the 50 km/h test is 0.67GN and the 60 km/h test is 0.66GN. This shows a speed dependency in the data i.e. the slower the test speed the higher the measured grip.

The data at 30 km/h and 50 km/h in Figure 4-7 shows isolated spikes in the data. The grip data can be seen reaching the maximum output value from the GripTester MK2. This indicates that the measuring wheel may have lost contact with the track surface. This is probably due to braking of the tow vehicle forcing the measuring wheel off the ground as the driver tries to maintain constant speed. The use of cruise control reduces this anomaly improving the quality of the dataset.

Figure 4-8 plots 30 km/h data measured in the racing line for 2 different visits to Knockhill. The plots initially follow similar trends. An average wet grip level of 0.69GN for 30 km/h Speed Test 1 and 0.72GN for 30 km/h Speed Test 2 was observed. The standard deviation is 0.118 and 0.107 respectively. However, the area from distance 846 m to 1106 m shows a different pattern. This suggests either the surface grip had changed or a slightly different racing line had been measured.

This highlights the importance of track position with respect to supposed measurement of just the racing line.

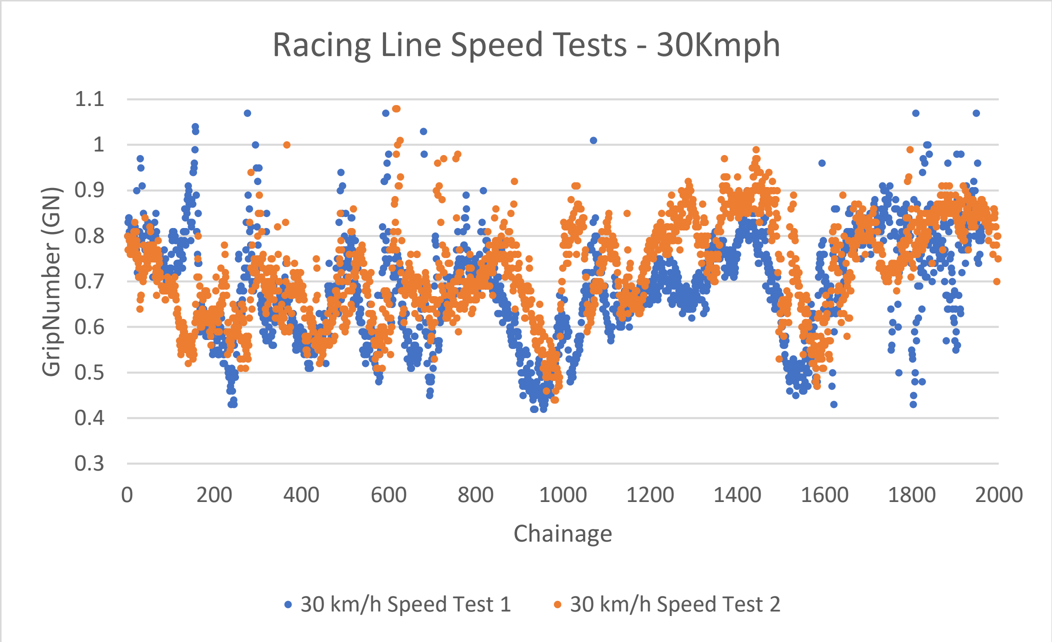


Figure 4-8 Comparison of 30 km/h speed tests

Figure 4-9 plots this speed test data in terms of cumulative frequency. This shows the 2 datasets recorded on different days at 30 km/h to be similar with some minor differences at the higher grip numbers. The differences in the data sets occur 0.65GN to 0.9GN data ranges. This could be a result of environmental conditions, track usage or the operator not following exactly the same line.

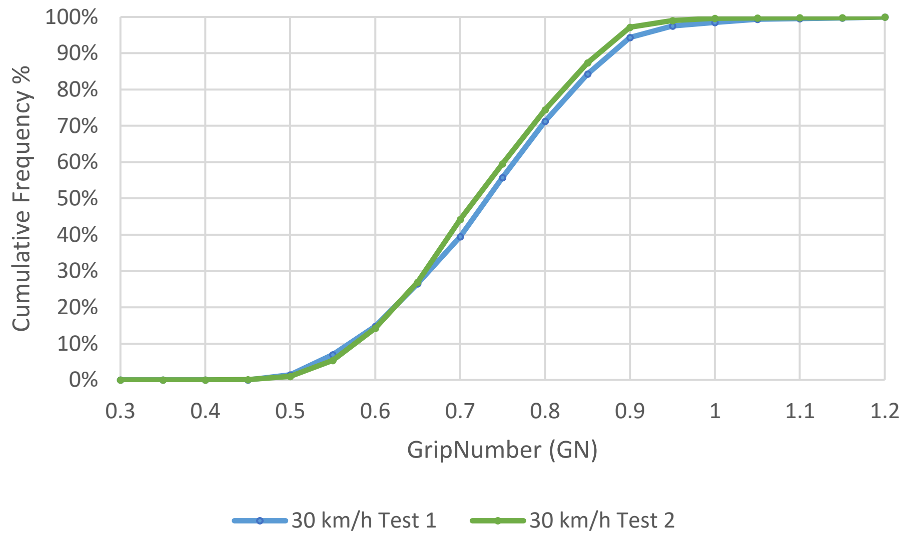


Figure 4-9 Speed Test Cumulative Frequency Analysis

4.4 The relevance of low speed grip data to high speed motorsport vehicles

A criticism of measuring grip at lower speeds such as 30 km/h is its relevance to the much higher speeds of motorsport. Figure 4-10 plots the average grip data for the speed testing at Knockhill. The maximum value that may be measured using a GripTester is 1.2 GN. The micro GripTester at 4 km/h produces a grip number that is 20% higher than the same surface tested with a GripTester MK2 at 50 km/h. This gives a micro GripTester data point of 0.85 GN at 4 km/h. Figure 4-10 plots speed against the micro GripTester data along with the GripTester data. This shows a power relationship with a R^2 value of 0.99.

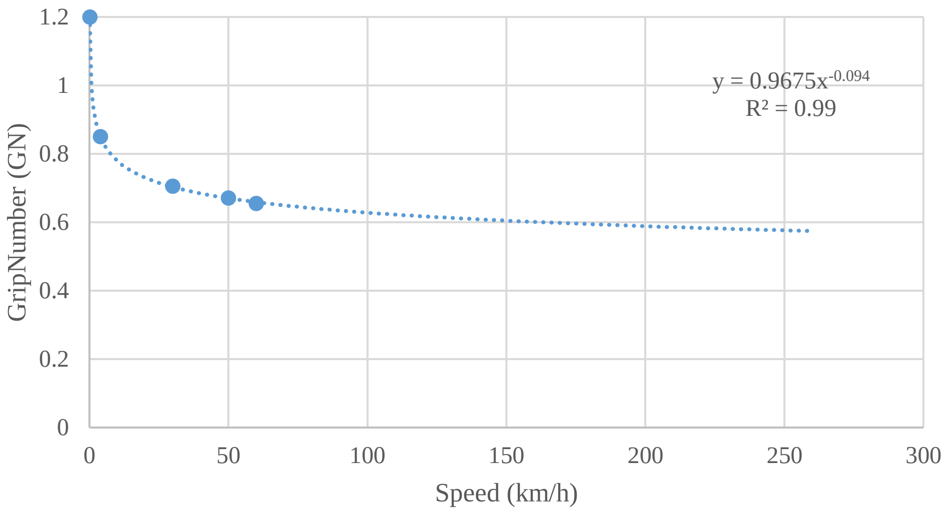


Figure 4-10 Grip data power interpolation for higher speeds

Figure 4-11 show power trend lines applied to the Nursetiawan (2008) data. This also shows strong correlations for all the road surfaces measured. It is suggested that use of a power relationship based on grip measurements at a range of lower speeds could possibly be extrapolated to consider how grip measured using a GripTester may change at the much higher speeds associated with motorsport. Further work is required to understand the effect of water displacement as the testing speed is increased. Proving the interpolation at higher speeds using standard CFME will be difficult due to the limitations of the devices and the towing vehicles.

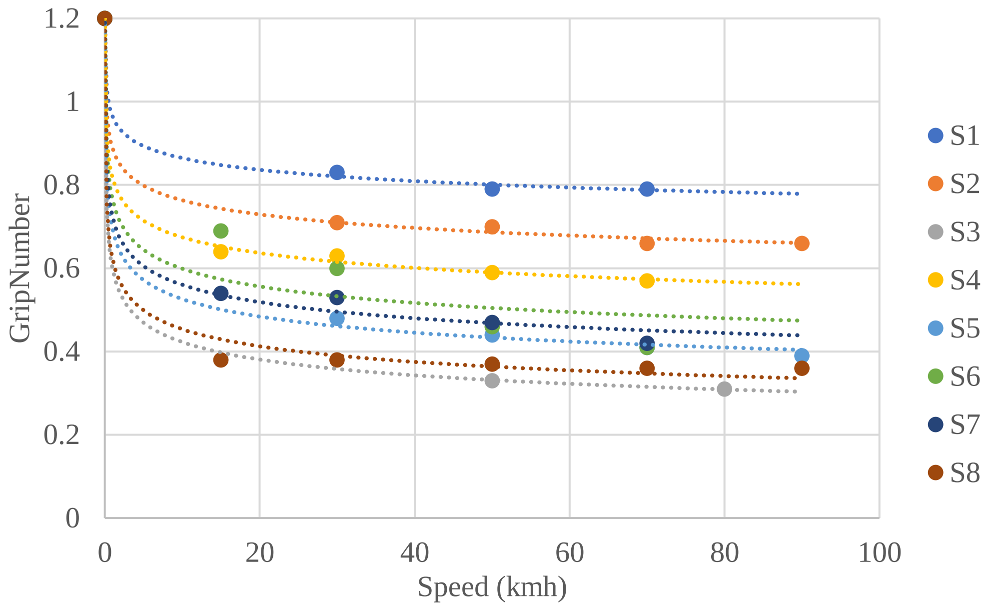


Figure 4-11 Power trend lines for the Nursetiawan (2008) data

4.5 Testing in dry and wet conditions

Most motorsport events take place in dry conditions. Racing in wet conditions increases the likelihood of accidents. Recent high-profile incidents such as the death of Jules Bianchi at the 2014 Japanese Grand Prix and the 2017 Italian Grand Prix where Roman Grojean aquaplaned on the main straight highlight the dangers of racing in wet conditions (Sam, 2019; Green, 2017). The 2018 Silverstone MotoGP race was cancelled due to safety concerns with the resurfaced track after incidents in the build up to the race which happened in wet conditions (Puigdemont, 2018).

Better understanding of wet grip could offer race stewards the ability to apply thresholds for levels of surface water on a circuit by circuit basis. This would allow a scientific approach for scenarios such as when to declare a wet race, tyre choice for wet conditions or when to stop a wet race due to excessive surface water.

Figure 4-12 shows the effect of water on GripTester data measured on a road surfaced with a short section of limestone aggregate (Woodward et al, 2012). The dry data shows a very small difference between the gritstone and the limestone. The wet data shows a significant difference. Both the gritstone and limestone road surfacing materials had good macrotexture. The difference in wet grip was caused by the limestone being polished and having almost no microtexture.

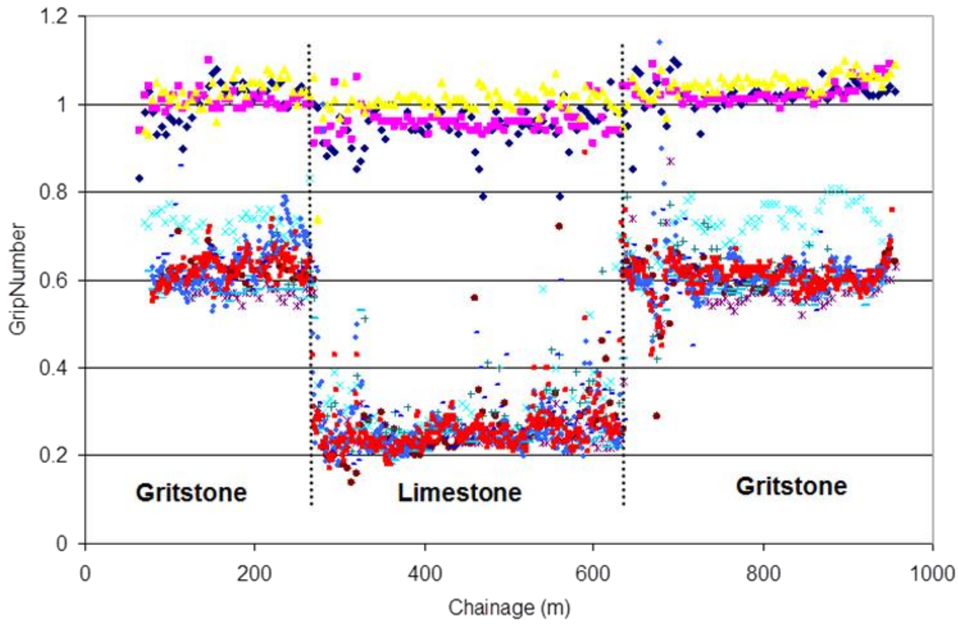


Figure 4-12 GripTester data showing effect of water and rock type (Woodward et al., 2012)

A comparison of dry and wet grip data is shown in Figure 4-13 for two laps of the racing line at the 2018 Singapore Grand Prix. The grip testing of roads and runways is always carried out in wet conditions. Dry testing can damage the test tyre. This example shows significant differences between dry and wet track surface conditions in the grip values measured. The comparison of dry and wet data shows dry testing may need to become an option.

Once a road or racetrack becomes wet it will lose grip. The 2017 Singapore F1 Grand Prix was the first wet race in the 10 years of the event. The race takes place at the beginning of the wet season when the country is prone to short, heavy tropical rain storms. Figure 4-14 shows the grip testing equipment parked up in the flooded pitlane.

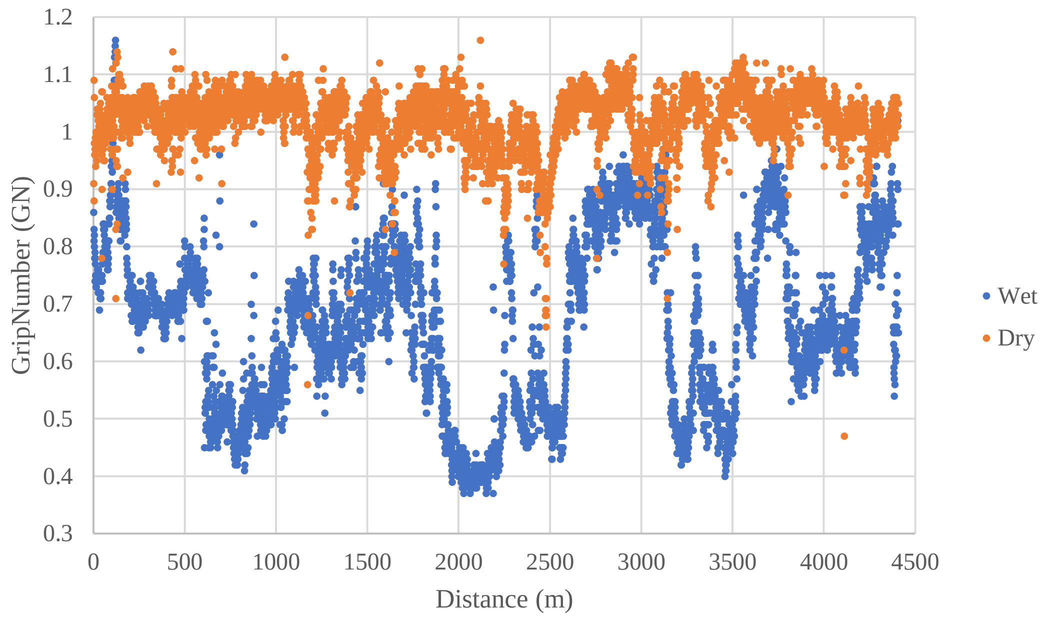


Figure 4-13 Comparison of dry and wet grip data before Qualifying at the Singapore Grand Prix 2017

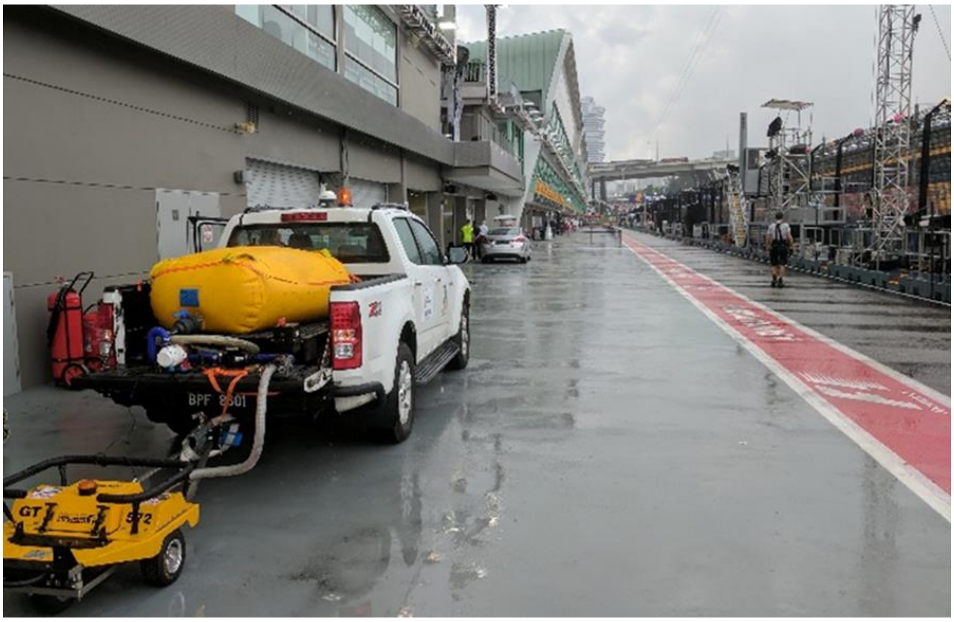


Figure 4-14 Flooded pit lane at Singapore Grand Prix 2017

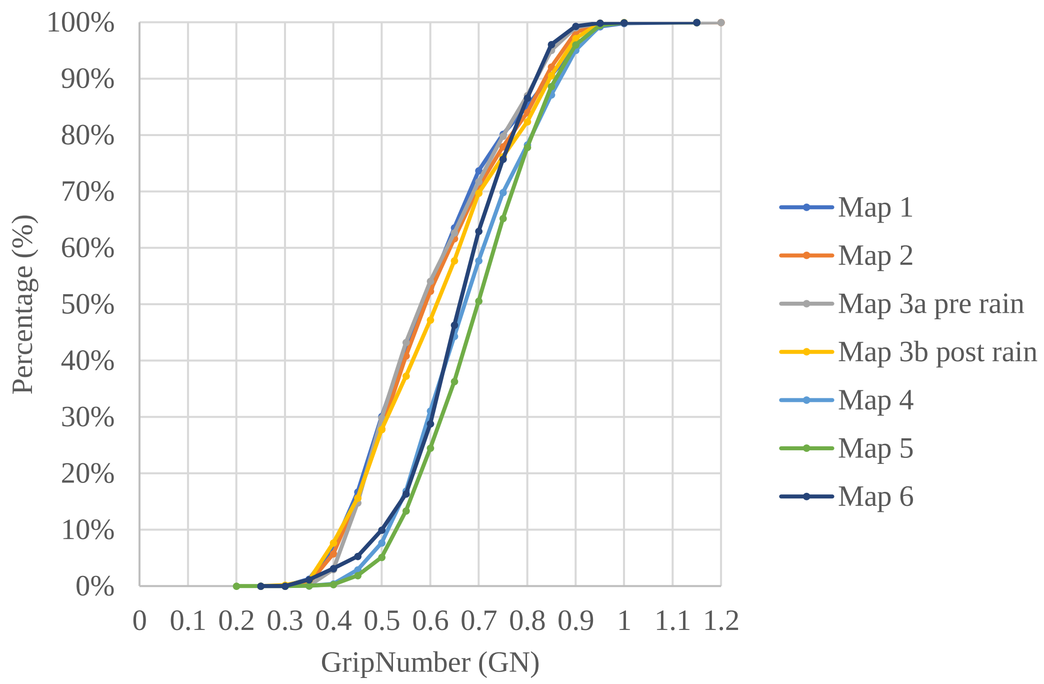


Figure 4-15 Singapore Grand Prix 2017 GripMap cumulative frequency analysis

Six grip surveys were completed throughout the 2017 Singapore Grand Prix week. Each grip survey measured up to 16 laps of the circuit and resulted in approximately 50,000 grip data points. The data is compared as a cumulative frequency analysis in Figure 4-15. There is a step change in the wet grip values between Maps 1, 2 and 3 compared to Maps 4, 5 and 6. The effect of the heavy rain is apparent in Figure 4-16.

Map 3a was measured before the tropical rain event and Map 3b was measured after the rain event had ceased. The track was drying quickly due to the 35°C air temperature when Map 3b was carried out with no standing water visible. No other vehicles were running on the track between Map 3a and Map 3b nor were any surface treatments. Therefore, the increase in overall grip for the track is a direct result of the rain on the surface and the washing effect.

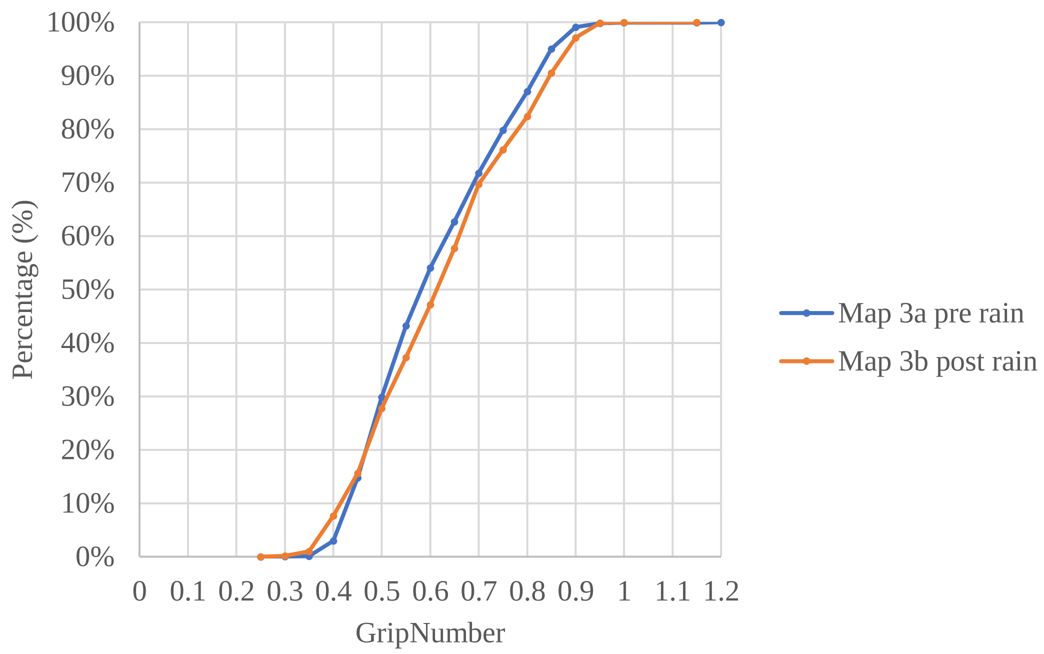


Figure 4-16 Singapore Grand Prix 2017 Map 3 before and after heavy rain

4.6 The GripMap Method to measure full racetrack grip variation

The GripMap Method (GMM) has been developed to address the knowledge gap for a standard test to measure the full test track rather than just the racing line. The GripTester MK2 has been identified as the most suitable CFME to carryout full racetrack surface grip surveys.

The trailer-based GT device is portable and can be transported around the world and deployed quickly with a suitable tow vehicle. In Figure 4-17, a GripTester is being unpacked in a pit garage at Yas Marina, Abu Dhabi after it had been shipped from the UK. This was the first time a GripTester had been shipped over-seas for the purposes of testing a race track. Based on this experience, the following is the minimum equipment required to conduct a full racetrack grip survey for GMM.

- GripTester.
- GripTester Calibration kit.
- GripTester tow hitch.
- Laptop.
- GripTester data collection software Roadbase © .
- Automatic Watering System (AWS) – consisting of a pump, flow meter, actuator valve, control box and relay box.
- Water tank/bladder or either 250, 500 or 1000 litres capacity
- RS232 to USB serial hub.
- GPS receiver.
- Tow vehicle.

Figure 4-17 Unpacking the GripTester at Yas Marina

Figure 4-18 GripTester and associated equipment at Singapore

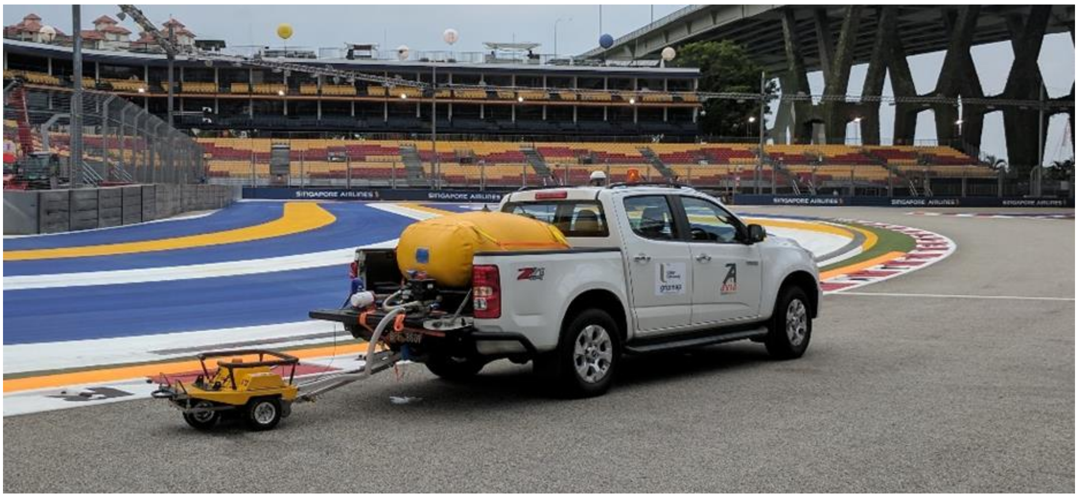


Figure 4-19 GripTester equipment and tow vehicle ready for a full racetrack grip survey

The test equipment is shown in Figure 4-18 and Figure 4-19 at the Singapore Grand Prix. The tow vehicle must be capable of holding the water payload safely and should have cruise control to maintain a consistent test speed of 30 km/h. The use of multiple tow points, one in line with the outside wheel, one in line with the inside wheel and a tow point in the centre of the vehicle is advantageous although not essential (see Figure 4-20). This makes it easier to align the GripTester to the edges of the track surface.

Figure 4-20 GripTester tow ball position plate

A standard Windows laptop running the proprietary Findlay Irvine GripTester Roadbase© software is required. An example screenshot is shown in Figure 4-21 during a GripMap survey of the Singapore Grand Prix circuit. The software must be configured to collect data at averaging lengths of 1m to ensure the maximum amount of grip data is collected. The software uses the GPS receiver to stamp GPS data to each recorded grip data point. The measured data is exported in a comma separated values (csv) format.

The test speed is 30 km/h. The water application rate is set to give a nominal water film thickness of 0.25 mm is 3.73 litres per minute. This means 500 litres of water is required to test approximately 67 km of track. The nominal water film thickness can be increased from the Roadbase© software directly. In most circumstances increasing the water film thickness should reduce the measured value of wet grip. This allows the standard GMM to be modified if required to assess the effects of water such as flooded track conditions resulting from heavy rainfall during a race event.

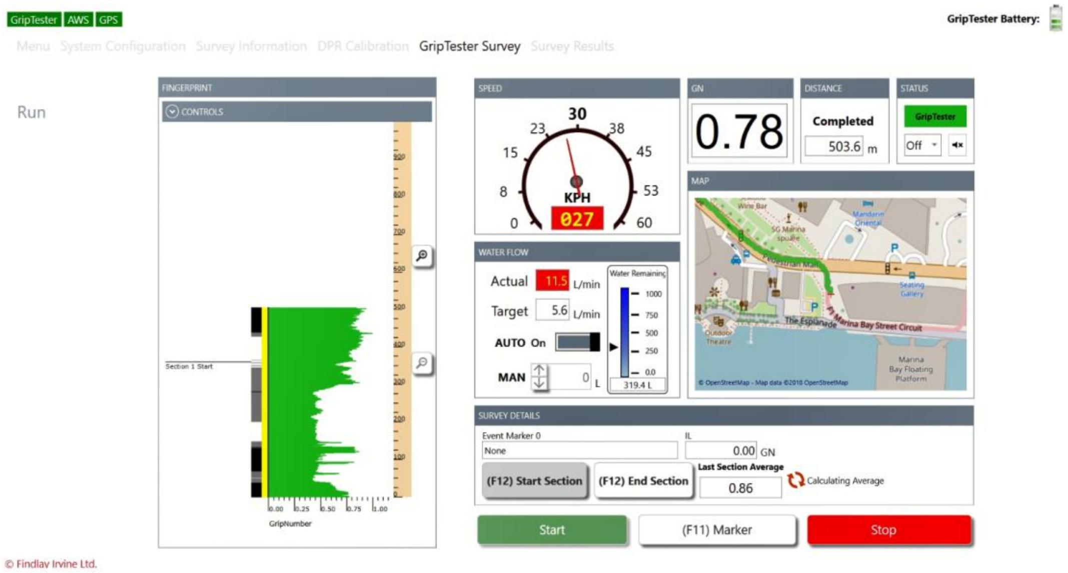


Figure 4-21 Screenshot of GripTester Roadbase© v2.0 software during measurement

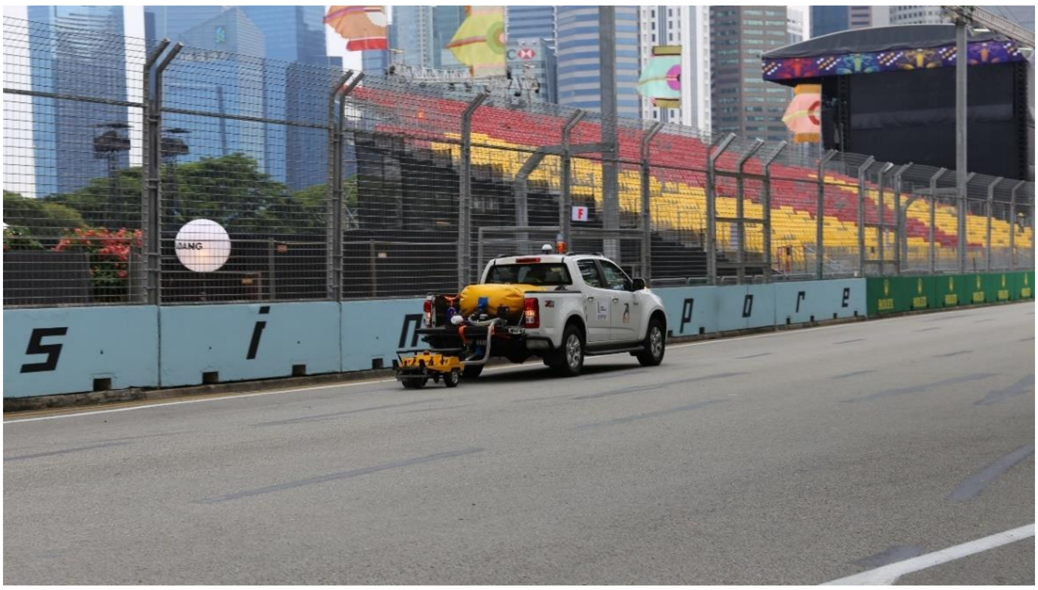


Figure 4-22 GripTester undertaking a first lap on the Singapore Grand Prix circuit

Grip testing starts at the inside left edge of the track, normally from the Start/Finish line. The first lap follows the edge of the track. The second lap moves across 1m and follows parallel to the first lap. Successive laps move across the full width of the track at nominal 1m intervals. Figure 4-22 shows the first lap of a GripMap survey. The survey is complete when the outside right hand edge line has been reached and completed for the full circuit. This process is designed to produce a series of nominally parallel lines at 1m intervals across the full width of the track from edge to edge. Figure 4-23 shows a set of nominally parallel lines at Donnington. Figure 4-24 shows an example of nominally parallel lines plotted in a GIS using the GPS co-ordinates.

It is important that the driver does not cross the line previously completed in order to keep the data from overlapping. Maintaining equidistance between successive lines can be challenging due to track geometry when the track is not the same width for the entire lap. It may not be possible to maintain a desired line if other work is going on at the track at the same time as the grip survey. In these scenarios, the best line possible should be followed. However, outlying data points can be removed during post-processing if necessary. The number of grip points in the completed survey may range from 50,000 to 80,000 depending on the racetrack characteristics.

Figure 4-23 A set of parallel test measurement lines at Donnington

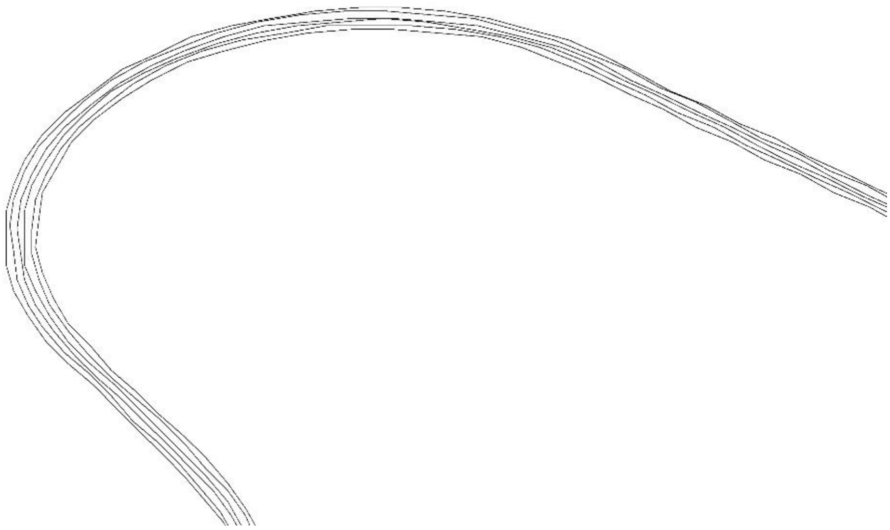


Figure 4-24 Parallel measurement lines plotted in a GIS

CHAPTER 5

HOW TO ANALYSE GRIP DATA

5 Chapter 5: How to Analyse Measured Grip Data

5.1 Introduction

This chapter details methods of grip data analysis. This ranges from examining small datasets from single laps to working with large datasets comprising of a full width GMM survey of a track using GPS stamped data.

5.2 How to analyse grip data

Selecting the most appropriate method of analysis depends on factors such as the desired outcome, the potential use of the data and the size of the data set. Part of a raw data file collected from grip a grip survey is shown in Figure 5-1. The Figure shows test data for just a few meters. The data includes chainage, GripNumber (GN), load acting on the test tyre, test speed, water flow rate, latitude, longitude and altitude.

A Comma Separated Values (CSV) dataset can be up to 100,000 records for a full track survey. These values can be analysed in different ways that can highlight relationships, patterns and variations across datasets.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	<HEADER>														
2	SWVersion	GTNumbe	GTMark	AxleType	TyreDetai	DPRDate	DPRResul	DPRLengtl	AverageL	Operator(	SurveyNa	TargetSpe	WaterFilm	SurfaceCo	Weather
3	2.0.0.4	GT572	MK2	D	A79-18072	08-May-18	0.7968	1000	1	5	Race Track	30	0.25	Dry	Clear and
4	<EMUSED>														
5	EMid	EMIndex	EMName	EMDirecti	EMLength	ILName	ILLevel	ILdescription							
6	<RESULTS>														
7	Chainage	GN	Load	Speed	Flow	EM Name	IL Level	Latitude	Longitude	Altitude	Quality	No. Satell	GPSTime	Duration	EM Used
8	1	1.05	18.88	0	30.3		0	1.29485	103.8629	7.4	1	10	51:06.6	3.108	
9	2	1.02	19.73	0	30.3		0	1.29485	103.8629	7.4	1	10	51:06.6	3.108	
10	3	1.05	20.55	0	8.6		0	1.29485	103.8629	7.4	1	10	51:08.0	4.465	
11	4	0.91	20.88	0	8.6		0	1.29485	103.8629	7.4	1	10	51:08.0	4.465	
12	5	0.6	20.07	4.7	5.6		0	1.29485	103.8629	7.4	1	10	51:08.6	5.14	
13	6	0.54	19.73	7	5.6		0	1.29485	103.8628	7.5	1	10	51:09.0	5.461	
14	7	0.65	18.24	7.3	3.9		0	1.29485	103.8628	7.5	1	9	51:09.5	5.966	
15	8	0.8	16.33	8	3.9		0	1.29485	103.8628	7.6	1	9	51:09.8	6.281	
16	9	0.93	18.53	8.3	9.5		0	1.294833	103.8628	7.7	1	9	51:10.6	7.066	
17	10	0.84	19.83	9	9.5		0	1.294833	103.8628	7.7	1	9	51:10.6	7.066	
18	11	0.74	18.45	9	9.4		0	1.294817	103.8628	7.8	1	9	51:11.6	8.056	
19	12	0.75	19.95	9.5	9.4		0	1.294817	103.8628	7.8	1	9	51:11.6	8.056	
20	13	0.72	20.16	10	9.5		0	1.2948	103.8628	7.8	1	9	51:11.9	8.375	
21	14	0.72	20.49	10	9.5		0	1.2948	103.8628	7.8	1	9	51:12.0	8.527	
22	15	0.7	18.71	11	9.7		0	1.2948	103.8628	7.8	1	9	51:12.4	8.907	
23	16	0.66	18.44	11.5	9.7		0	1.294783	103.8628	7.9	1	9	51:12.7	9.227	
24	17	0.59	20.99	11.7	9.6		0	1.294767	103.8628	7.9	1	9	51:13.1	9.556	
25	18	0.58	17.75	12	9.6		0	1.294767	103.8628	7.9	1	9	51:13.2	9.737	
26	19	0.61	21.32	12.7	9.2		0	1.294767	103.8628	7.9	1	9	51:13.6	10.064	
27	20	0.68	21.03	13	9.2		0	1.29475	103.8628	7.9	1	9	51:13.7	10.231	
28	21	0.68	20.49	13.7	9.4		0	1.29475	103.8628	7.9	1	9	51:14.1	10.561	
29	22	0.64	18.31	14	9.4		0	1.29475	103.8628	7.9	1	9	51:14.2	10.728	
30	23	0.64	19.12	14	9.5		0	1.294733	103.8628	7.9	1	9	51:14.5	11.039	
31	24	0.68	19.22	14.5	9.5		0	1.294717	103.8629	8	1	9	51:14.9	11.363	
32	25	0.74	18.79	15	10		0	1.294717	103.8629	8	1	9	51:15.0	11.524	
33	26	0.74	21.34	15	10		0	1.294717	103.8629	8	1	9	51:15.2	11.683	
34	27	0.72	18.53	16	9.9		0	1.2947	103.8629	8	1	9	51:15.5	11.999	
35	28	0.75	18.44	16	9.9		0	1.2947	103.8629	8	1	9	51:15.7	12.163	
36	29	0.73	18.6	16	9.9		0	1.294683	103.8629	8	1	9	51:16.0	12.492	
37	30	0.71	21.54	17	9.6		0	1.294667	103.8629	8	1	9	51:16.2	12.653	
38	31	0.73	18.52	17	9.6		0	1.294667	103.8629	8	1	9	51:16.3	12.804	
39	32	0.77	17.09	17	9.6		0	1.294667	103.8629	8	1	9	51:16.5	12.961	

	P	Q	R	S	T	U	V	W	X
2	AmbientT	SurfaceTe	Operator	StartDate	StartTime	SurveyLer	Comment	Units	Filename
3	30	33.8	CW	14/09/2018	21:50:52	4154		M	180914 Full gri

Figure 5-1 Example CSV file output from a GripTester survey

5.3 Analysis of small grip datasets

Examples of how to use smaller sample sized datasets has been discussed in Chapter 4. Analysis tools in programs such as Microsoft Excel can be used to quickly analyse grip data. Figure 4-4 Racing line speed testing recorded 6 Aug 2015 illustrated how such tools can be used to analyse the effect of speed on measured wet grip. This example used data from one lap of the racing line each completed at a different speed, generating approximately 2000 data points per lap. The scatter plot illustrates the variation in grip caused by the change in speed.

A scatter plot can be used to visually compare the repeatability of a grip survey. Figure 5-2 shows an example of two laps of the racing line at Knockhill Racing Circuit. The data was collected for two laps on the racing line from the Start/Finish line at 30 km/h both under dry conditions. The close agreement of the two plots suggests the repeatability of the method.

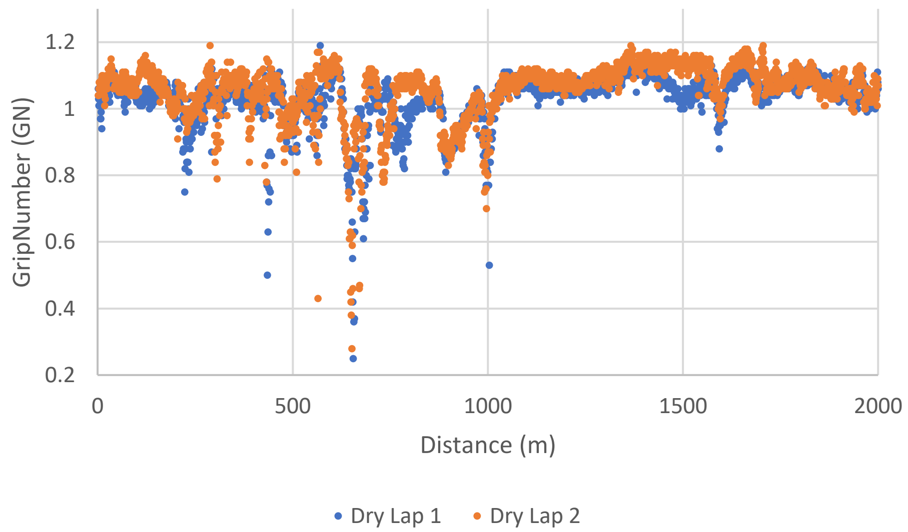


Figure 5-2 Comparison of the scatter plots of two laps of grip data from the racing line under dry conditions

This same data can be plotted allowing comparison with a lap of the track where a water film thickness of 0.25mm was applied to the tyre/surface interface. As the datasets are small they easily accommodate this type of visual comparative analysis to spot trends in the data. However, if many plots are added to a scatter graph the result can become confusing and challenging to interpret. For example, Figure 5-3 shows longitudinal grip at four equal distances through a series of corners at Yas Marina (Woodward et al., 2012).

Using this method of plotting GN and distance for a full track grip survey does not produce an output that is easy to analyse. Figure 5-4 is an example of a full track grip survey of Knockhill Racing Circuit data plotted as a scatter graph with 20,000 grip data points. Although this allows comparison of the grip data for the 10 laps it is difficult to relate each data point to its actual track position.

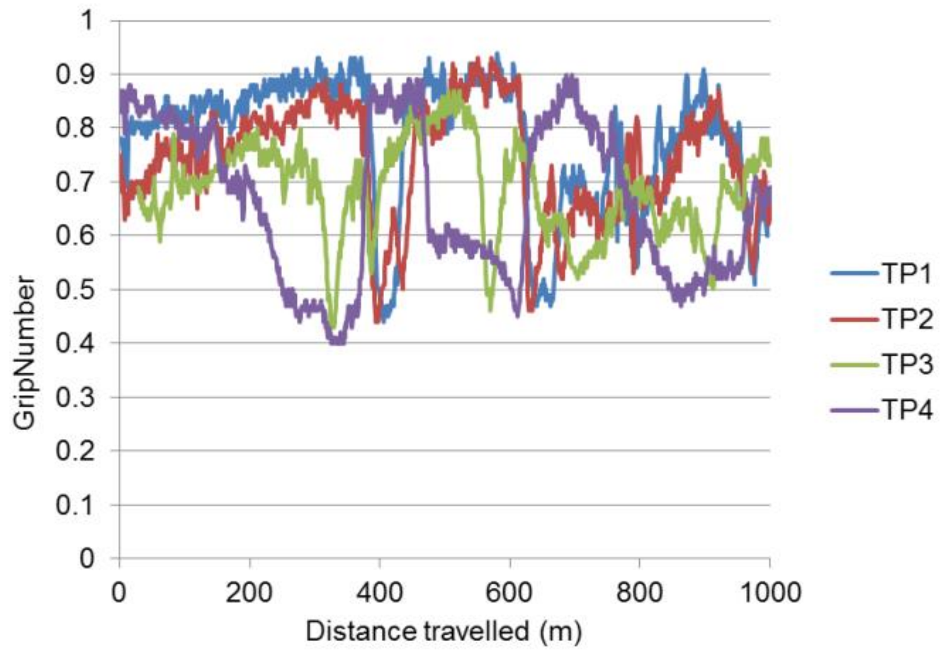


Figure 5-3 Variation in longitudinal GripNumber at 4 equally distances across the width of a race circuit going around a series of corners (Woodward et al., 2012)

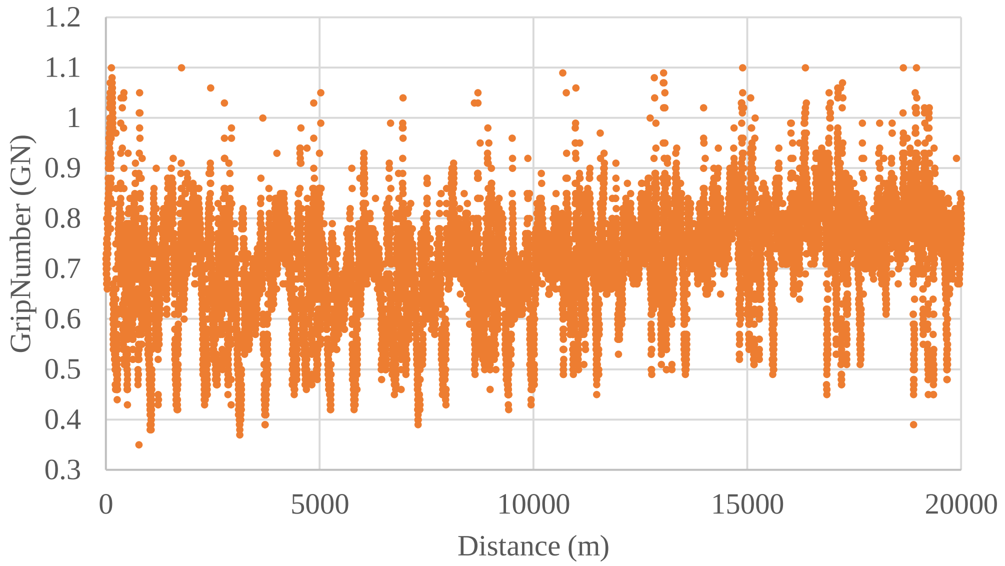


Figure 5-4 Scatter plot of a full GripMap survey with over 20,000 grip data points

5.4 Analysing large datasets

Large datasets from full GripMap surveys need to be considered as a whole to best identify relationships and variations over time or over the course of a race event. The data can be analysed using simple statistics including calculation and comparison of mean grip values for whole datasets. For example Figure 5-5 shows a plot of mean GNs from surveys conducted at Knockhill Racing Circuit between November 2014 and September 2016.

Each value is the mean of approximately 20,000 individual grip measurements for each survey over this two-year period. The mean values plotted in this way suggest a decline in measured wet grip. However, the two surveys BTCC 15 After and BTCC 16 After were completed immediately after busy race weekends when the track was heavily used, resulting in a reduction of measured wet grip. This is apparent in the mean values for BTCC 15 Before and After. Other variables such as seasonal variation and environmental conditions will affect measured wet grip surveys.

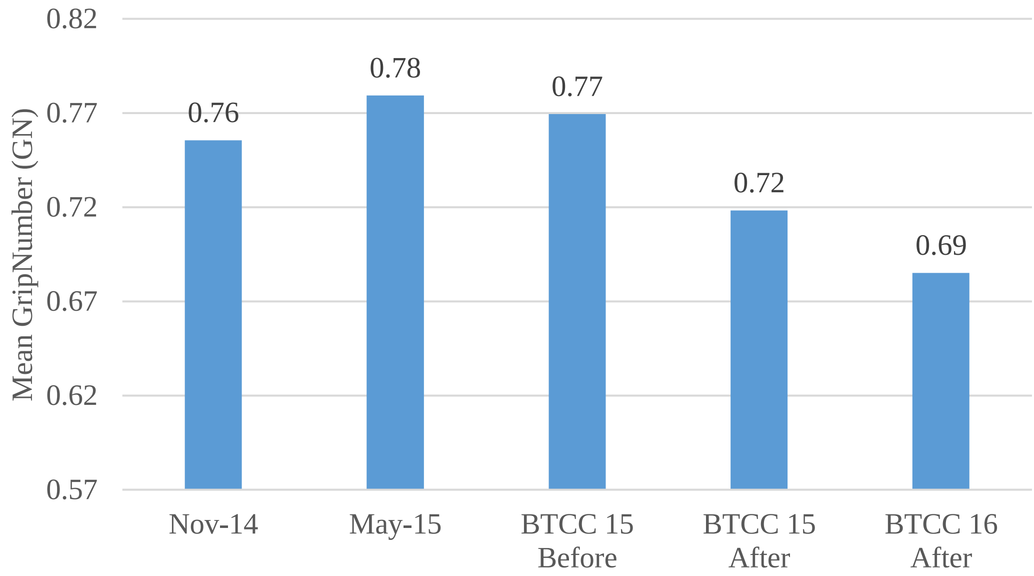


Figure 5-5 Mean GN values for grip surveys conducted at Knockhill Racing Circuit between 2014 and 2016

Plots of GN frequency distribution can be used to compare multiple datasets and visually identify any overall changes. Figure 5-6 plots Knockhill survey data from 2009 to 2016 which shows how the wet grip has changed for the track. The frequency distributions show a similar pattern and shape with an overall decline over this period from 2009 to 2016. This would be expected for any road or race track as the aggregate becomes polished and the asphalt reduces in wet grip to equilibrium. The reduction in wet grip observed in BTCC 15 After and BTCC 16 After is a direct result of the racing event where greater tyre/surface interaction has occurred across the whole of the track. Both GripMap surveys were completed directly after the British Touring Car Championship (BTCC) events in 2015 and 2016.

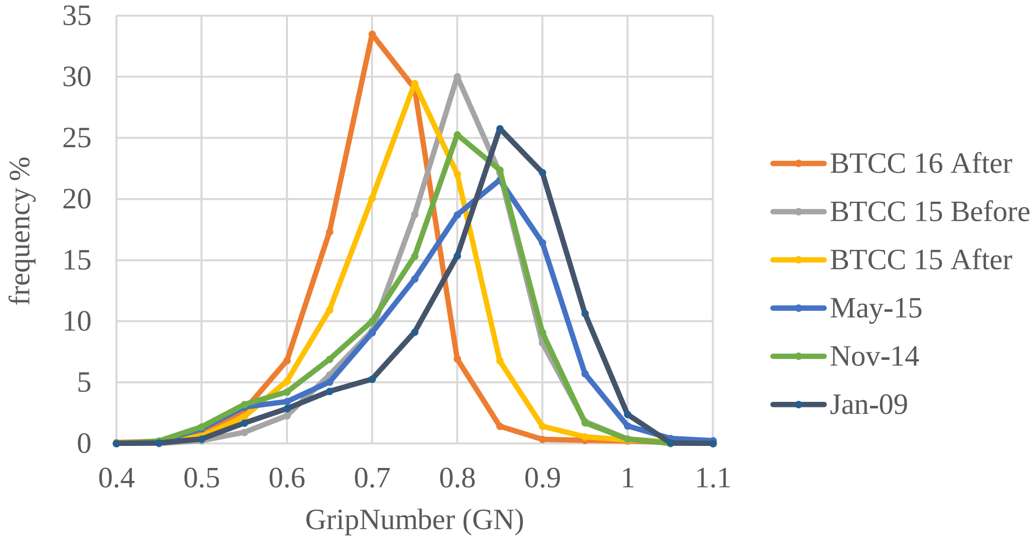


Figure 5-6 Frequency distribution analysis of Knockhill GripMap survey data from 2009 to 2016

Figure 5-7 compares the frequency distribution for data measured before and after the BTCC Knockhill event in 2015. This illustrates how racetrack grip can evolve during a single weekend event. Data can be plotted as a cumulative frequency plot as shown in Figure 5-9 which is derived from the same data as Figure 5-7. Figure 5-8 is a cumulative frequency comparison of the data used in Figure 5-6. Both methods allow the same data to be visualised in different ways.

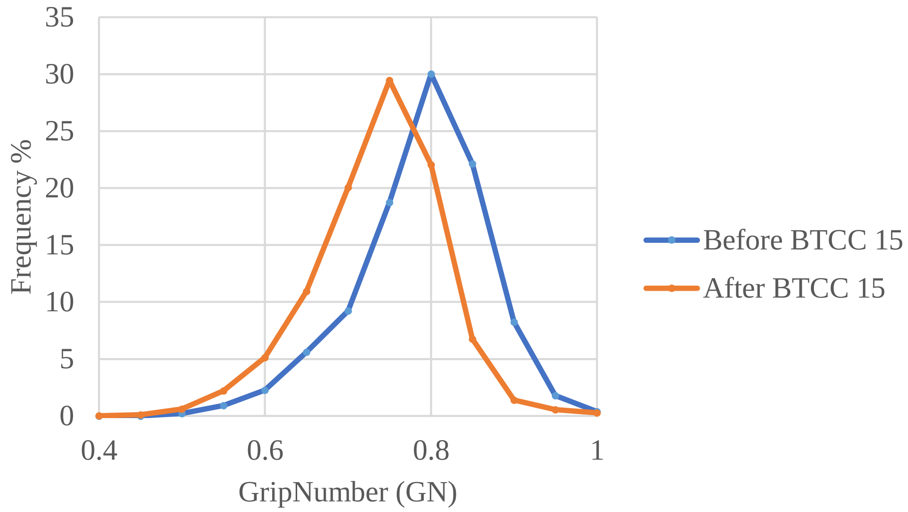


Figure 5-7 Frequency distribution analysis of GripMap dataset before and after the Knockhill round of the 2015 BTCC event

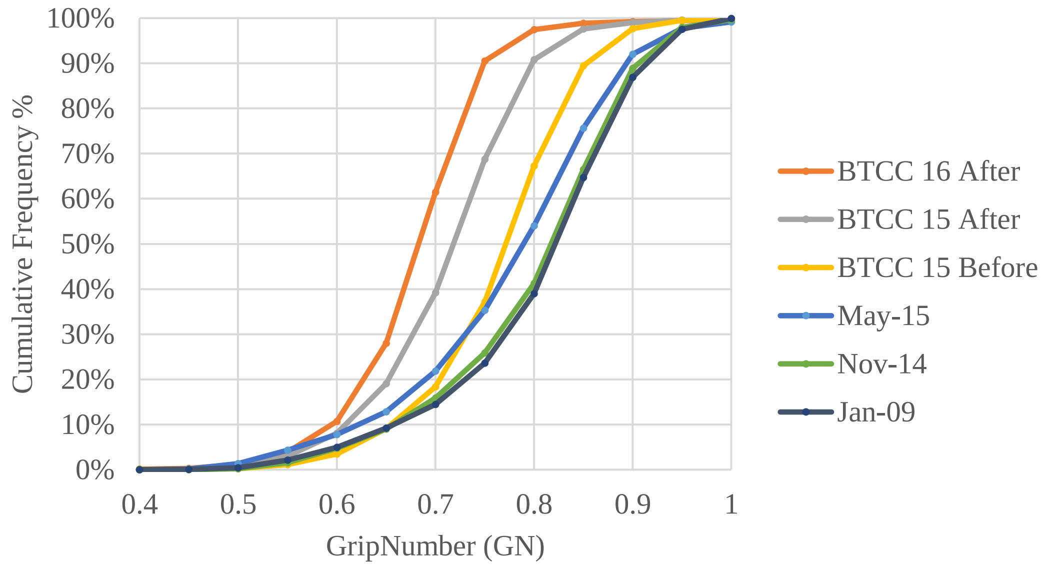


Figure 5-8 Cumulative frequency analysis of Knockhill GripMap survey data from 2009 to 2016

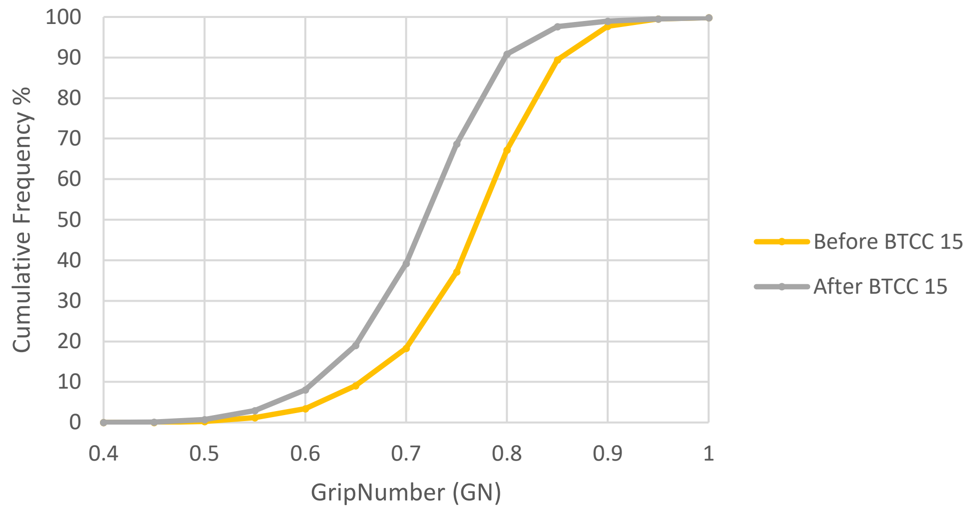


Figure 5-9 Cumulative frequency analysis of GripMap dataset before and after the Knockhill round of the 2015 BTCC event

The kurtosis and skewness of the frequency distributions can be calculated using Excel in order to analyse the weight of outlier values at the extremities of the measured wet value ranges (kurtosis) and the symmetry of the data range (skewness). Table 5 compares Skewness and Kurtosis values for the Knockhill surveys carried out before track events. The Kurtosis for each survey is negative and the distribution is skewed to the left of the median, towards the lower ranges of the overall data set. The Skewness values for Nov-14 of -0.59 and -0.56 for May-15 are similar, suggesting a similar pattern in the dataset with a comparable spread of recorded frequency of measured wet grip values.

Table 5 Kurtosis and Skewness for Knockhill GripMap surveys 2014 to 2016

GripMap Survey	Skewness	Kurtosis
Nov-14	0.76	-0.59
May-15	0.42	-0.56
BTCC 15 Before	1.64	-0.29
BTCC 15 After	2.91	0.12
BTCC 16 After	8.09	0.51

5.5 Contribution of GPS to visualisation of grip data

Grip data recorded using GripTester includes latitude and longitudinal co-ordinates. Use of a 10 or 20 Hz receiver means that each GripNumber is assigned a unique set of coordinates when the test speed is 30 km/h and the data is averaged every 1 m. This allows plotting grip to generate maps that allow better visualisation of the data using mapping software such as Google Earth, Google Maps, MATLAB, ArcGIS, Civil 3D, MapInfo, SAGA GIS and QGIS.

The large datasets generated by full grip surveys can be processed efficiently and can be georeferenced to other types of spatial data such as satellite images or CAD drawings. Figure 5-10 is an example of a GripMap from a wet grip survey at Yas Marina F1 Circuit, Abu Dhabi (Woodward, Millar and Waddell, 2012).

Figure 5-10 GripMap showing variation in longitudinal and lateral wet grip at Yas Marina F1 circuit corners 1, 2 and 3 (Woodward et al., 2012)

The GripMap has been superimposed on a Google Earth image. Colour thresholding has been used to show variation in wet grip. Features of the racetrack surface such as the racing line is visible in the GripMap. Red shows areas of low wet grip caused by increased tyre/surface interaction as vehicles brake hard, engage a turning motion resulting in increased lateral tyre/surface action, before accelerating at the point of the apex of the corner. The blue and black parts of the track indicate areas of the highest wet grip which are off the racing line and rarely trafficked.

Interpolation of measured wet grip data for a racetrack is different to roads and airports. Low wet grip for a road suggests a slippery surface and higher risk of having an accident. Low wet grip for a race track is considered as high grip by racing drivers driving in dry conditions.

5.6 Use of Excel to produce a GripMap

There are two main methods that can be used to plot grip data using the GPS data in Microsoft Excel. Early GripMaps created by Ulster University used Microsoft Excel. Latitude and longitude data was extracted from the GripTester .csv file along with the grip data in the GN column. The longitude data is set to the x axis and latitude to the y axis. Selecting the latitude and longitude columns and then inserting a scatter plot will create a visual representation of the spatial data. Figure 5-11 shows the result of the plotted data using the GPS data.

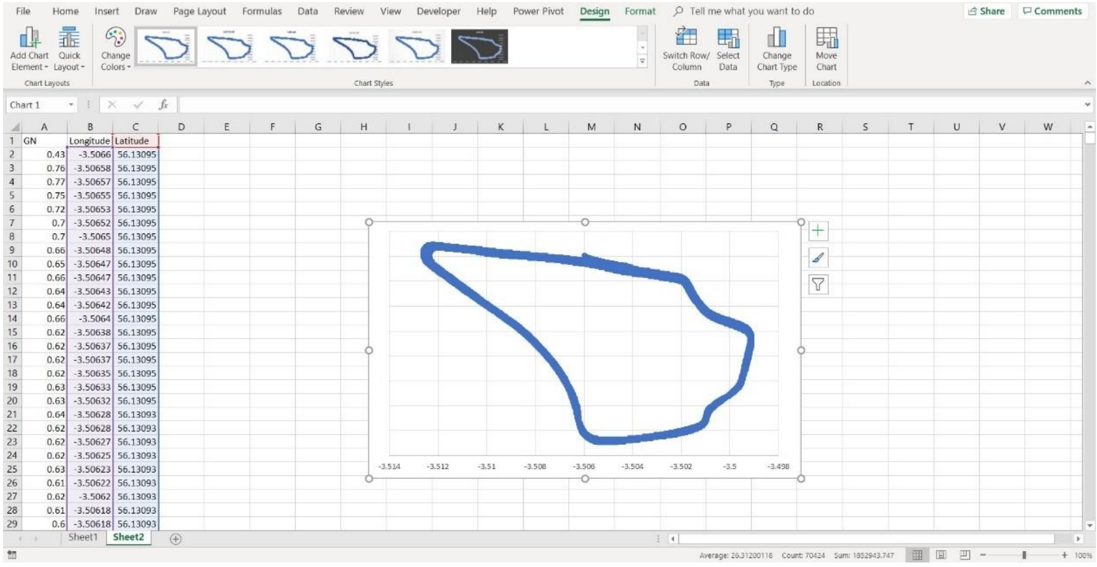


Figure 5-11 Excel plot of GripMap data

Colour thresholds can be applied to the grip data in the GN column can using a macro script or Visual Basic. A colour-based threshold banding can be applied to show variation in grip data. A GripMap can be created using Excel Power Pivot and 3D Map add-ins. The add-ins must be installed using the Add-Ins manager in the Options menu. The same data set will be used as shown in Figure 5-11. The data must be transformed into a Power Pivot table by highlighting the data columns then selecting the Add Data to Model function in the Power Pivot menu. The result is shown in Figure 5-12.

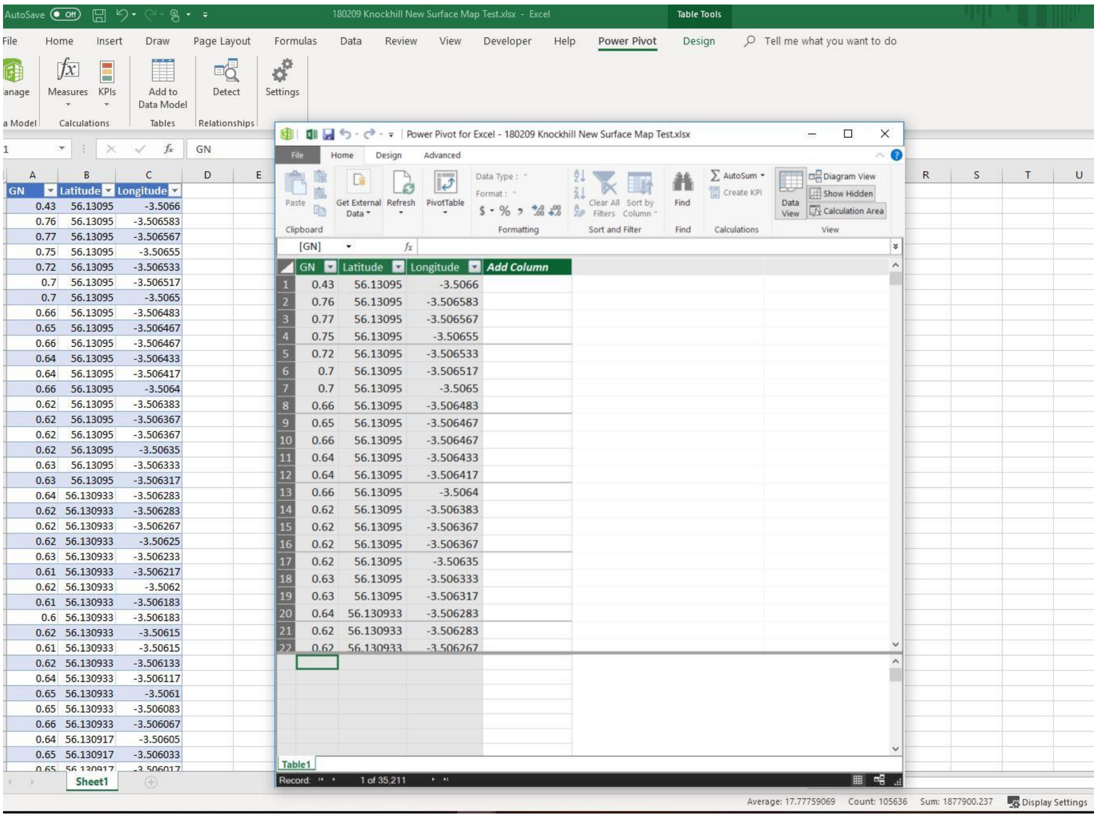


Figure 5-12 Example of GripMap data transformed into a Power Pivot table using Excel

A GripMap can then be created using the Power Map functionality from the 'Insert' menu and selecting '3D Map'. This will then plot each row of data on a map from the latitude and longitude data. The data is displayed on a map as a layer. The layer menu, displayed on the left of Figure 5-13, allows the grip data to be filtered and the manner in which it is displayed can be changed.

Initially, the data is displayed as a bar chart on a map. By selecting the heat map option, a GripMap can be created. The GN data, or any column of data from the Pivot Table to be analysed, should be added to the 'Value' option. The software will use this column as the variable to associate with the spatial data. Figure 5-13 is an example of an unfiltered GripMap created using this technique.

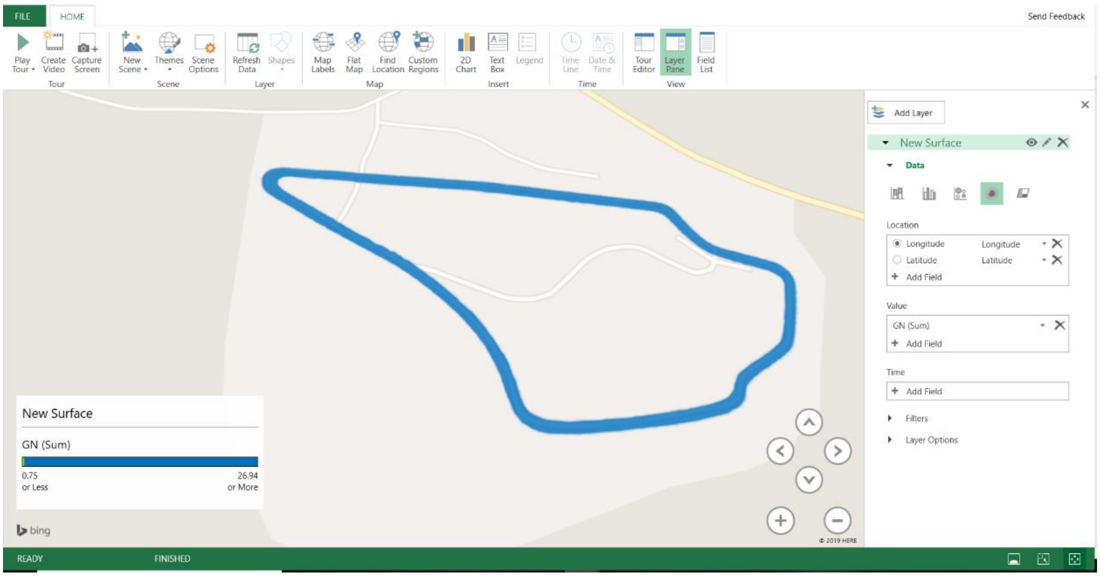


Figure 5-13 Unfiltered GripMap created using Excel Power Map

Filters can be added to the grip (GN) data field if it has been selected as the 'Value' option. This allows the data to be better visualised using colour coded thresholds. The thresholds can be adjusted to look for patterns such as low and high areas of measured grip. Figure 5-14 illustrates how the same GripMap appears with the thresholds adjusted. Braking zones in the approach to corners and a racing line are visible.

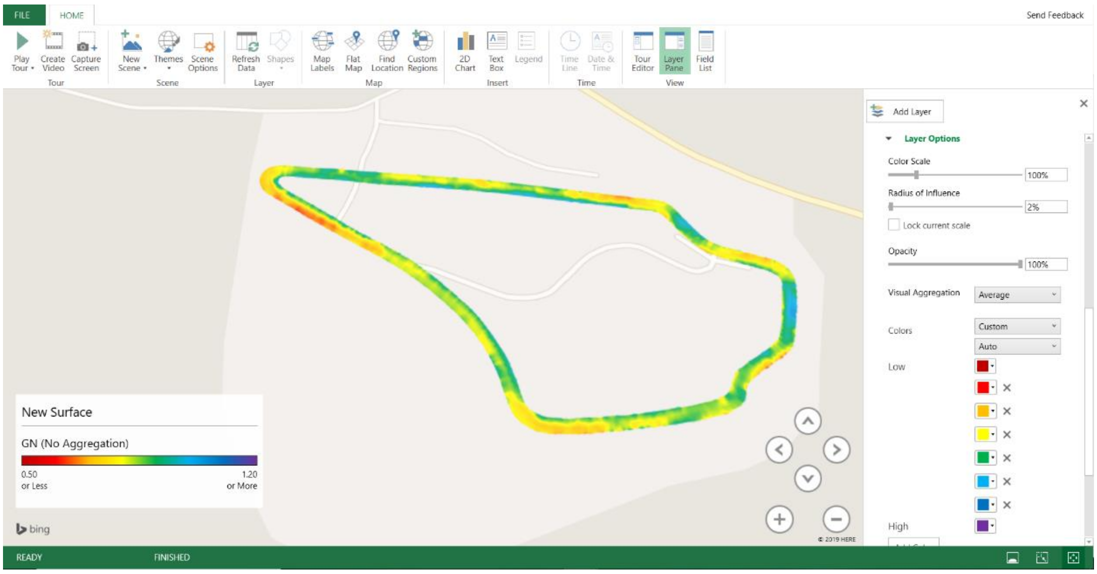


Figure 5-14 GripMap with applied colour thresholds adjusted using Excel Power Map

This method allows a GripMap to be exported as a screen capture. Figure 5-15 is an example of a full GripMap output after full track resurfacing with limited vehicle trafficking. This method can be used to quickly compare GripMaps. Figure 5-16 is the same track after high-pressure water texturing had taken place to remove excess bitumen from the asphalt surface. This is highlighted in the larger areas of blue/green.

Figure 5-15 GripMap screen capture using Excel Power Map

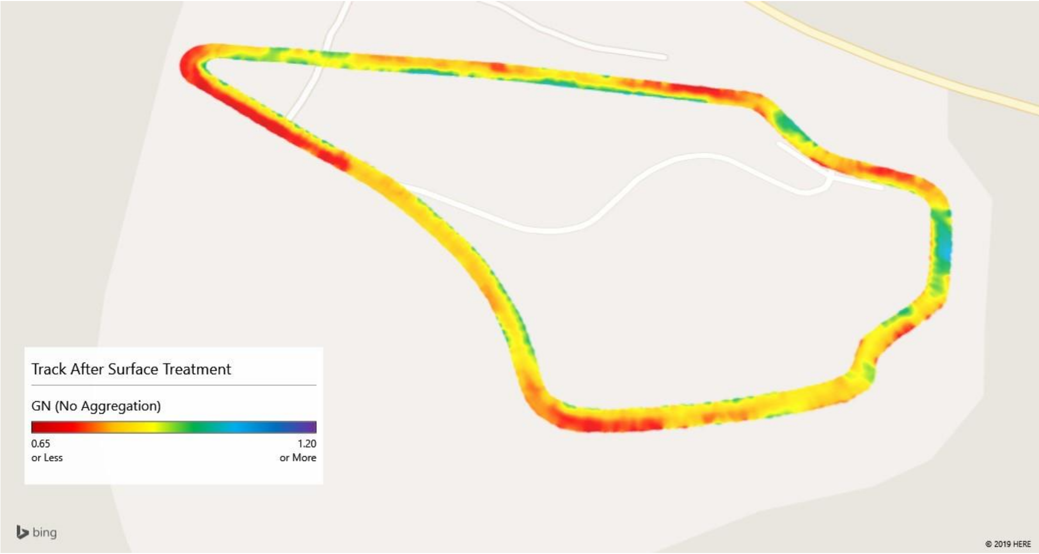


Figure 5-16 Example of GripMap screen capture export after surface treatments using Excel Power Map

5.7 The use of ArcGIS software to create a GripMap

Although Excel Power Maps can quickly generate a basic GripMap it does not have the functionality to query the data set. ArcGIS software developed by the Environmental and Social Research Institute (ESRI) was selected for fuller analysis due to its large array of tools, options and ease of use. ArcMap allows grip data to be imported from GripTester software in either CSV format or SHP format.

A detailed description of how to use ArcGIS software to create a GripMap can be found in Appendix A. How to create a GripMap using ESRI ArcGIS software.

5.8 Practical uses for GripMap in motorsport

A GripMap can track evolution of track grip through a race event. Information such as threshold ranges, orientation and borders can be included for presentation purposes. Figure 5-17 shows a GripMap completed before the start of the 2015 BTCC Knockhill event. The track was at its natural grip equilibrium. Figure 5-18 is a GripMap based on grip measurements after the race event. The track is trafficked in a clockwise direction. A reduction in grip is visible and can be attributed to the tyre/surface interaction of the vehicles throughout the race event.

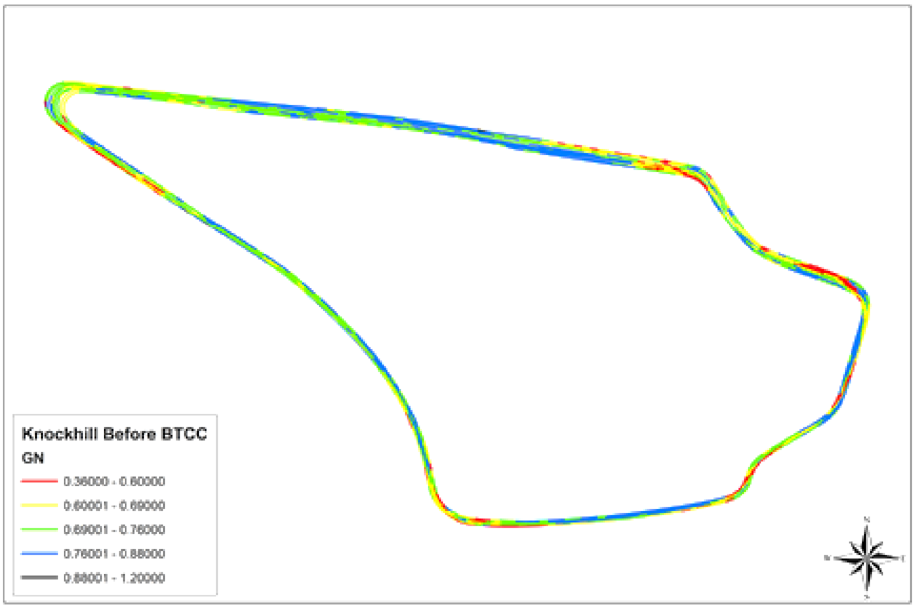


Figure 5-17 Knockhill before BTCC 2015 event

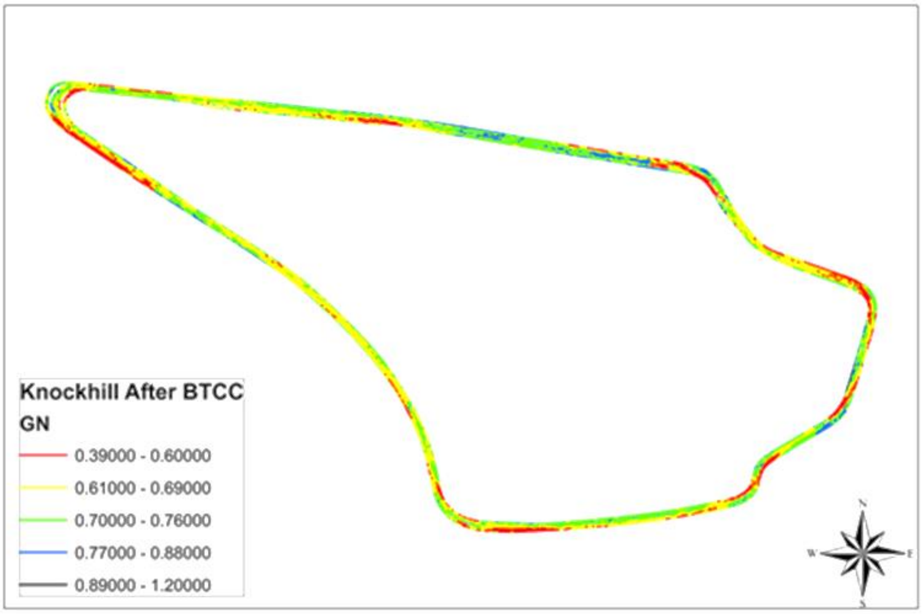


Figure 5-18 Knockhill after BTCC 2015 Event

Reductions in grip are present all around the track surface, particularly on the racing line and in areas of high stress. Figure 5-19 shows the reduction of grip at the Hairpin. The colour thresholds used to represent wet grip levels are the same as shown in Figure 5-17 and Figure 5-18. Increased areas of red, which represents the lowest threshold of wet grip, can be seen in the braking zone. This is also visible just after the apex of the corner and on the exit where vehicles are accelerating at full throttle.

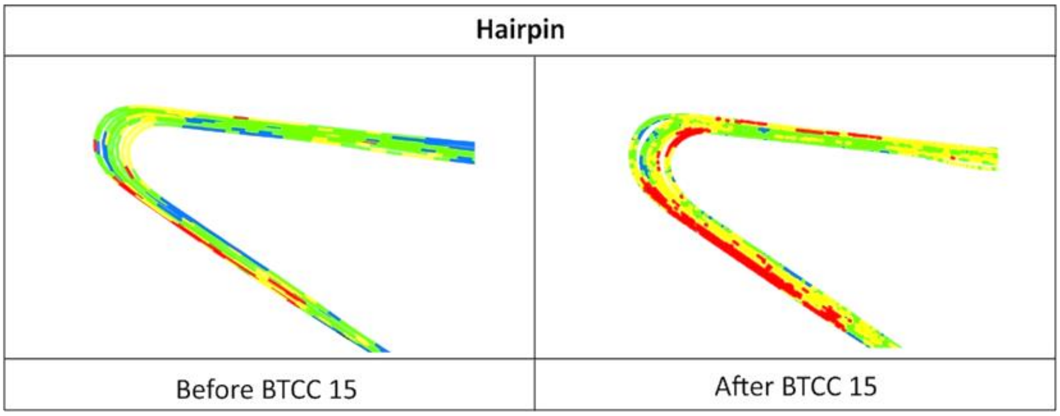


Figure 5-19 Knockhill Hairpin GripMap before and after BTCC 2015 event

Figure 5-20 shows a GripMap before the start of the 2017 Singapore Grand Prix event. A map of the Singapore Grand Prix Marina Bay Circuit highlighting corner numbers and key features is shown in Appendix A. Different surface materials, ages and conditions can be identified by the grip levels shown. Older surface materials are more polished and have lower grip levels, examples are displayed in red and yellow. Turn 6 to Turn 8 show varying levels of wet grip from higher levels of above 0.75GN to lower levels below 0.45GN along the straight and approaching Turn 8.

The variation is clearly visible across the GripMap surveys completed throughout the race event as shown in Figure 5-20, Figure 5-21 and Figure 5-22. The effects of high-pressure water retexturing treatment used to clean the surface and remove excess bitumen from new surface material, tyre/surface interaction and rain can all be seen in the GripMaps.

Figure 5-20 Base GripMap before track is handed over to the Race Director

Figure 5-21 GripMap before high pressure water retexturing treatment

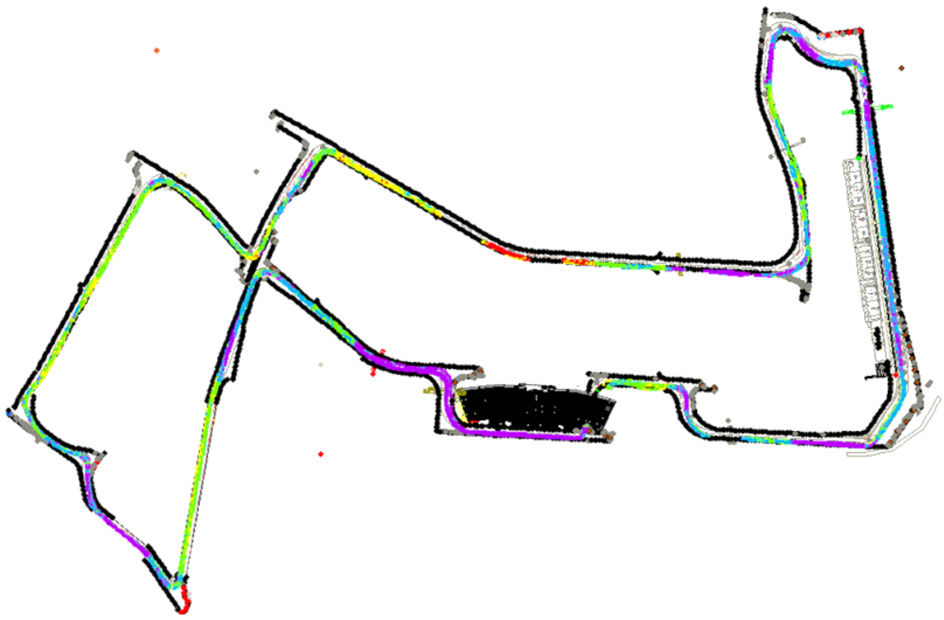


Figure 5-22 GripMap after qualifying and rain storm

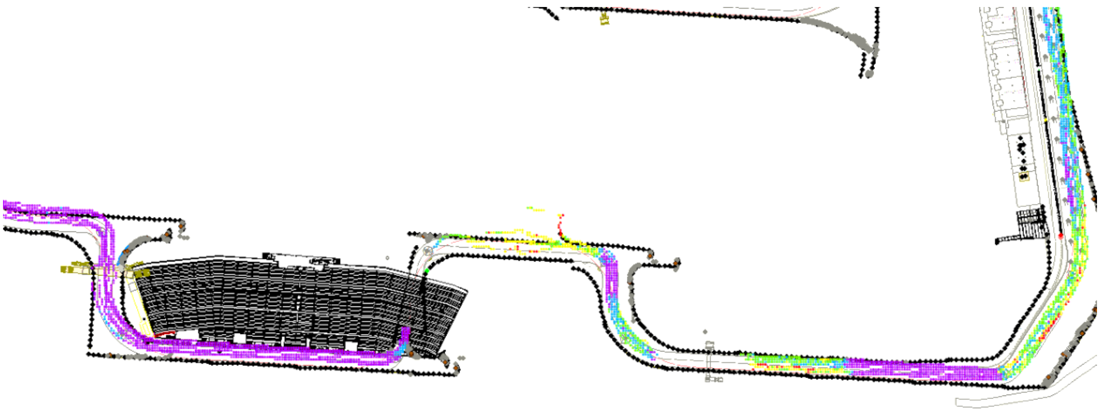


Figure 5-23 Singapore Grand Prix 2017 Turns 17 to 23 pontoon section before the race event

Figure 5-23 shows a GripMap from the Singapore Grand Prix 2017 Turn 17 to 23. The sections that have been treated with the RoadGrip Trackjetting high pressure water retexturing process are shown in purple. The grip level is significantly higher to that of the untreated areas.

The recently resurfaced area around the pontoon area was treated with high pressure water retexturing process before the GripMap survey. This area provided grip readings above 0.80 GN which is consistent with a high grip surface in a road or airport context. The sections between Turn 19 and Turn 20 show a lower level of grip. This area was in the 0.45 GN to 0.55 GN range. This would be considered as requiring investigation in a road context (DRMB HD28, 2015). This area of lower grip may have an influence on a vehicle's tyre/surface interface when transitioning across the surface from the area of higher grip.

On the permanent track sections that have not been treated by the retexturing process, the racing line from previous years is visible. This can be seen between Turn 21 and the purple, high grip, retextured section and on through the final two corners onto the main straight. This is identified by the red and yellow areas which show a lower level of wet grip on the vehicles optimal route.

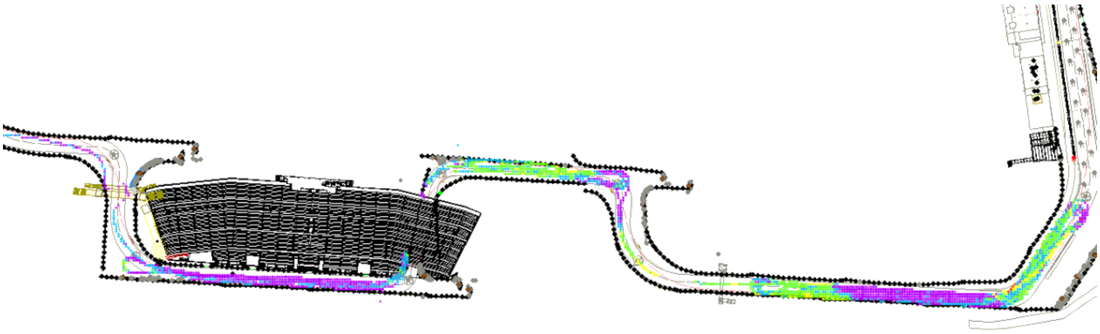


Figure 5-24 Singapore Grand Prix 2017 Turns 17 to 23 pontoon section after the race event

Figure 5-24 illustrates the changes to the track surface after the race event. Despite the wet conditions of the Formula One event, the formation of a racing line is seen to be developing. This may be observed as the development of blue areas with 0.65 GN – 0.75 GN through the pontoon section. This is where the surface grip is starting to decrease This is repeated in the section before Turn 22 which had been retextured.

The visualisation of measured surface grip data has potential for multiple uses. Newly laid asphalt surface material, whether full track resurfacing projects or patches can be evaluated using the GMM. Understanding track evolution could prevent issues associated with new track surfaces, such as the concerns voiced by the motorsport community surrounding 2018 pre-season F1 testing Barcelona and with the 2018 Silverstone track surface. The GMM can identify areas of low or inconsistent grip. Targeted treatments, such as high-pressure water retexturing, can be used to improve the grip. Highlighting areas of deficient grip, or large variations in grip, could help focus and so reduce maintenance costs for the track operator.

CHAPTER 6:

MEASURING LOCALISED RACETRACK GRIP USING A PUSH CFME MICRO GRIPTESTER DEVICE

6 Chapter 6: Measuring Localised Racetrack Grip Using Push CFME

6.1 Introduction

Measuring grip of a full racetrack surface using the standardised GripMap Method (GMM) at 30 km/h might not always be practical or applicable. Having the ability to measure racetrack grip in a localised targeted way is advantageous for several reasons. For example, motorsport teams may be allowed to inspect a racetrack for a limited time period only. A targeted approach to examine areas of particular interest identified from a full GripMap survey may be required. These include but are not limited to painted areas, run off zones, kerbs or the lateral grip profile across a racetrack. This chapter outlines how areas of interest may be investigated using the push CFME micro GripTester device.

6.2 The use of micro GripTester to measure racetrack grip

The use of the micro GripTester in motorsport is growing. FIA Formula E teams for example are known to measure grip of racetracks with a micro GripTester. Figure 6-1 shows a micro GripTester being used at the Mexican Formula E track. Formula E events take place on street tracks over the course of a single day. Unlike a typical F1 circuit, the street surface is not prepared in any way and can be made up of multiple surface materials of varying types and qualities.

Figure 6-1 micro GripTester being used to test a Formula E racetrack (DSTecheetah Instagram, 2019)

The teams have a 90-minute window before the start of the event to walk and evaluate the track. The micro GripTester is used to measure grip variation on the racing line by a team member manually pushing the device around the entire track. For example, the Mexico Formula E track is 2.093 km in length comprising of four surface materials with different grip characteristics. The grip data is then input into the car ahead of the race event. However, it is not known how the grip data is used by the cars' systems.

The micro GripTester has also been used in the FIA World Rally Cross (WRX) racing series. WRX events take place on short tracks that start on a solid material such as asphalt or concrete and move onto loose material such as gravel. Races normally last around four minutes. Teams are allowed a one-hour practice session and the event consists of knockout rounds of short races. The start of a WRX race is critical as the order that the cars navigate the first corner is normally the order in which they finish the race. Figure 6-2 presents an example of grip data of a WRX event starting grid measured with a micro GripTester. The position of the vehicles tyres is marked and the grip around them. This kind of data can be used to improve tyre traction and the vehicle launch process.

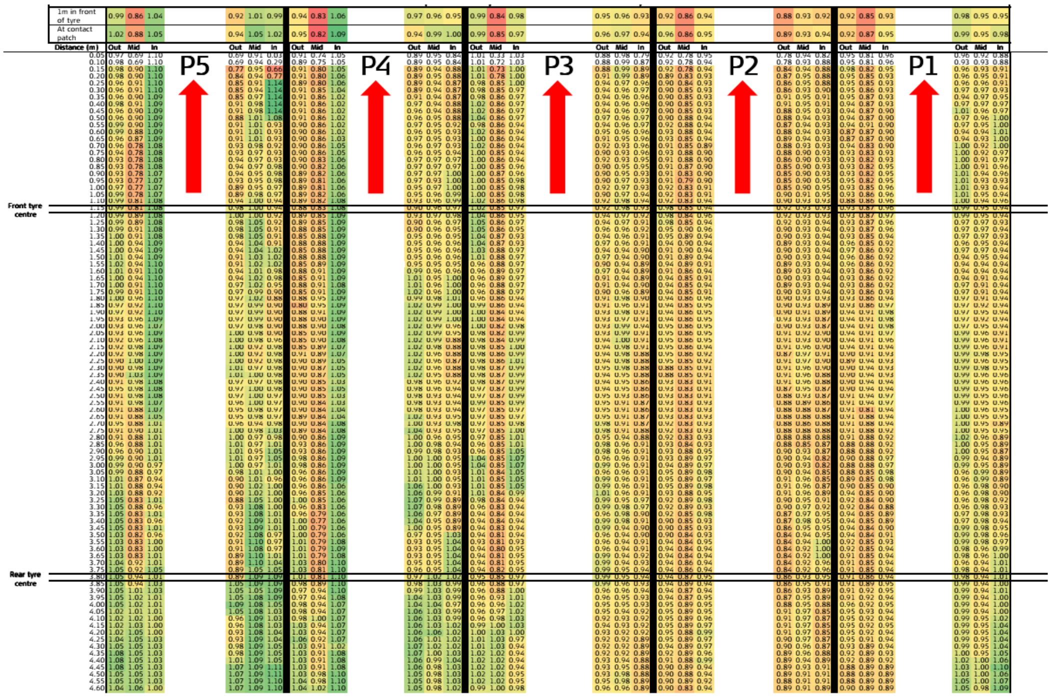


Figure 6-2 Example of grip data of a WRX event starting grid measured with a micro GripTester

6.3 Localised lateral grip measurements for an area of high stress

The micro GripTester was used at the Singapore Grand Prix 2017 to investigate how grip evolved at areas of high stress. The following example summarises the work carried out at Turn 14. The location of Turn 14 is shown in Figure 6-3. This corner has a heavy braking zone at the end of a long straight, a tight apex and exits onto a straight. Thus, Turn 14 was selected for its potential for significant and rapid changes of grip level to occur. Turn 14 also included a large patch of newly laid asphalt on the racing line that would be heavily trafficked.

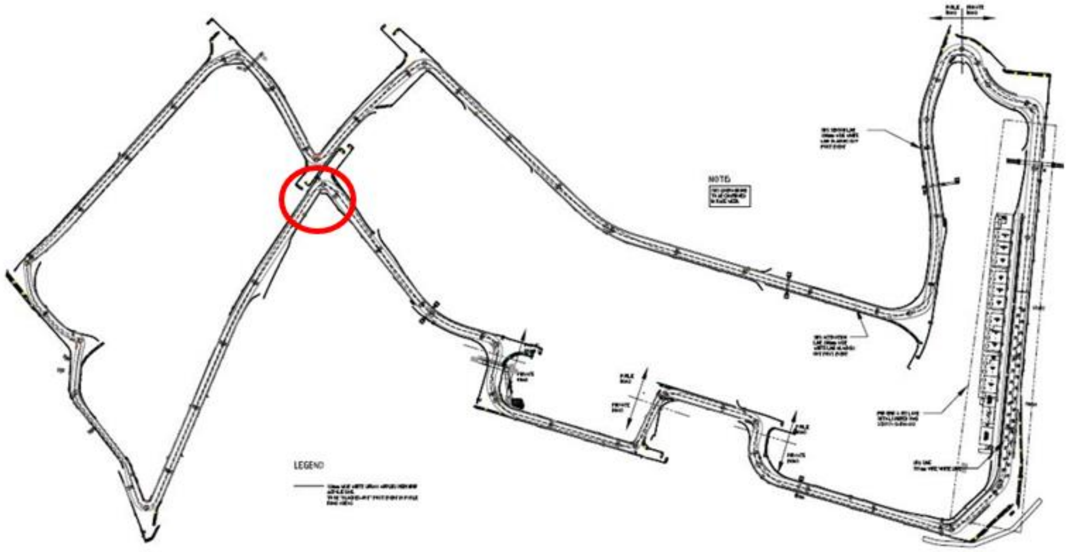


Figure 6-3 Singapore Grand Prix Marina Bay circuit showing Turn 14

Turn 14 is located at the end of the third longest straight in the circuit where cars are approaching 320 km/h before braking heavily into a 90 degree right hand corner and accelerating into a short straight away towards Turn 19. This is shown in Figure 6-4 and Figure 6-5. Vehicles approaching the corner are reaching maximum speed shortly before braking heavily around 50 m before the turning point, then turning right, riding the inside raised kerb at the apex and accelerating through the corner and out towards the opposite wall before continuing to accelerate away. The track surface in this area is therefore subject to high stresses.

Figure 6-4 Panoramic view of Turn 14 looking down Raffles Avenue and Esplanade Drive

Figure 6-5 View along Esplanade Drive in direction of travel

The corner at Turn 14 is part of the highway section of the track and is used throughout the rest of the year as part of the Singapore highway network. The long approach straight is part of Esplanade Drive and the corner is situated at the junction where Esplanade Drive meets Raffles Avenue. As this surface is otherwise normally trafficked throughout the year, the surface has been constructed to withstand normal highway use as well as the extreme forces from the racing vehicles throughout the Singapore Grand Prix event.

The surface at Turn 14 was consistent with the material used at other highway sections of the track. The material used is a 6/8 mm asphalt concrete with Shell Cariphalte binder. Visually the surface looked to be consistent throughout the tested area. Evidence of rutting in the wheel tracks was apparent in the lane markings across the surface. A new patch was laid on Raffles Avenue at the apex of the corner to the centre of the track measuring around 20m then extending along the inside right of the track for approximately 100m. The initial remedial patch had been laid six weeks prior to the event but was replaced two days before the start of racing due to rutting and material failure. A nominal 10mm size aggregate was used with an unmodified bitumen. The new patch is shown in in Figure 6-6.

Figure 6-6 New surface patch laid at the exit of Turn 14

The micro GripTester was used to traverse key locations through Turn 14. Three micro GripTester surveys across the patch were completed throughout the race weekend. Table 6 details the results of the grip surveys. The start point for each run was on the inside track limit line and the micro GripTester was pushed in a straight-line across the surface towards the outside track limit line. A grip data point was recorded every 48 mm. The location of each run is shown in Figure 6-7. The micro GripTester results were expected to be around 20% higher than GripTester values due to the differences in test speed.

Table 6 Turn 14 micro GripTester details

Survey Identifier	Date	Start Time	Ambient Temperature	Comments
microGT Survey 1	14/09/2017	01:55	30.8 ℃	Straight after patch had been laid, before Trackjetting
microGT Survey 2	16/09/2017	00:16	30.4 ℃	After practice, before qualifying and after Trackjetting
microGT Survey 3	18/09/2017	02:11	31.1 ℃	After Grand Prix

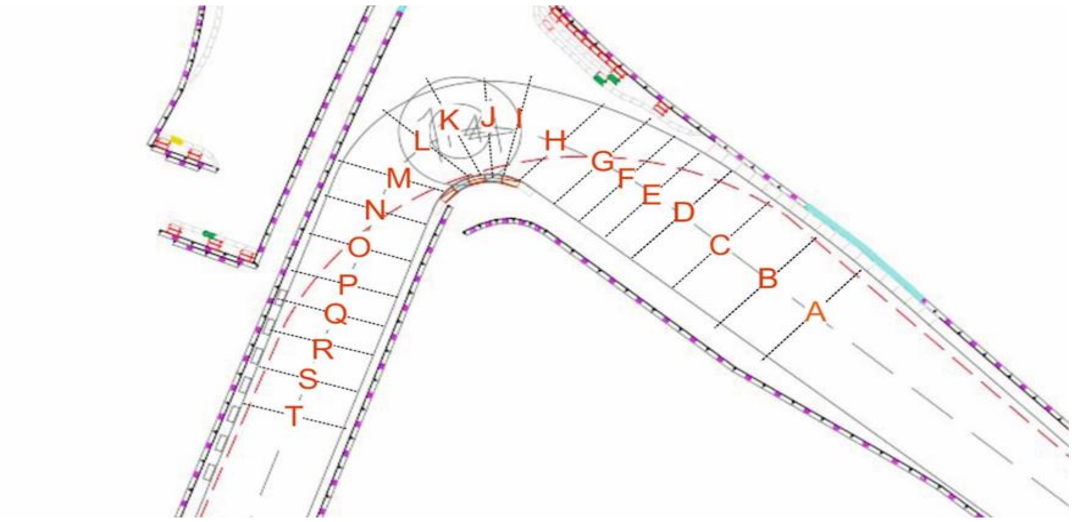


Figure 6-7 Singapore Grand prix 2017 Turn 14 lateral grip survey run locations

The Turn 14 micro GripTester data showed lateral grip to decrease throughout the race event. Significant changes in grip were observed. The data for all runs measured on each date were combined and plotted as a Cumulative Frequency graph as shown in Figure 6-8. Plots for the first (microGT Survey 1) and second (microGT Survey 2) micro GT surveys show little variation. However, the plot for the third micro GT (microGT Survey 3) is significantly different showing how the asphalt concrete at Turn 14 has changed as it was trafficked during the race event.

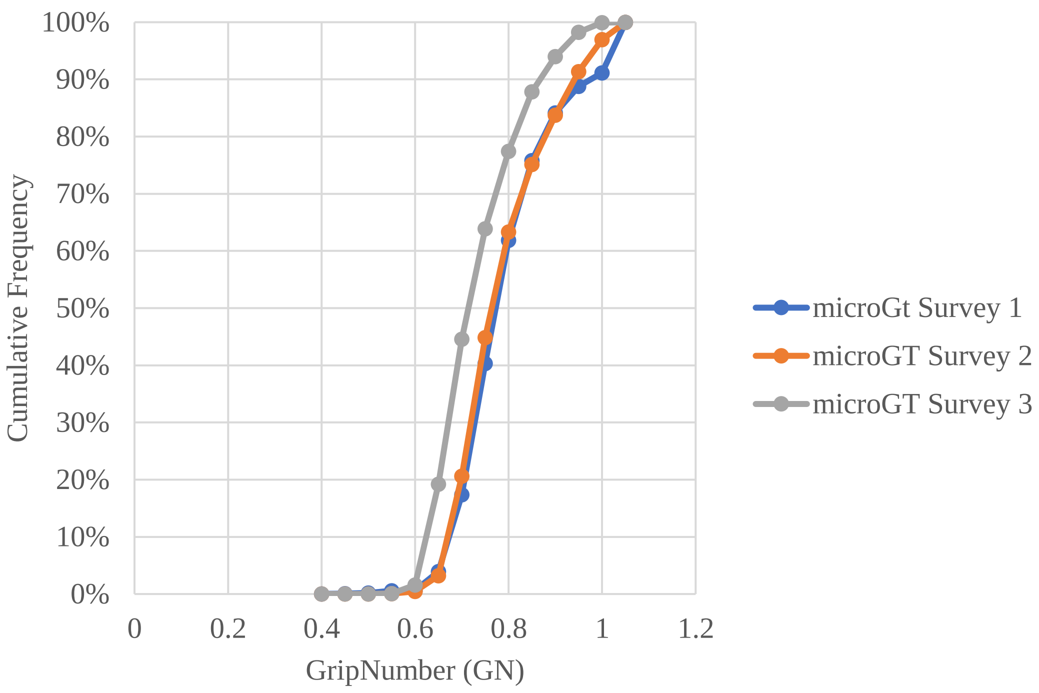


Figure 6-8 Cumulative Frequency graph for all runs measured on each date

The data showed a variation of grip over the different surfaces around Turn 14. The approach to Turn 14 was lower in grip than for the two different surface materials on the exit of the corner. The entry and braking zone surfaces were on average 0.08 GN lower than the asphalt at the apex and exit. This represents a difference of 9%.

Figure 6-9 plots the lateral grip data for Position C. This shows how the measured grip at this location evolved through the race event. Features from the highway are visible from chainage 170 to 320 in all three grip surveys. The troughs illustrate wear on the wheel path from highway trafficking of the road surface. The peaks around 226m, 271m and 304m occur where high friction paint has been used to cover white highway paint markings.

The area of consistent high lateral grip from 0m to 150m coincides with the new asphalt patch. The asphalt concrete was still hot after compaction at the time of microGT Survey 1. Figure 6-10 shows a photograph of the asphalt concrete immediately after the wet grip run.

The variation in grip between micro GT Survey 1 and micro GT Survey 2 is a result of the high pressure water retexturing surface treatment. Figure 6-11 shows the water retexturing treatment. The drop in measured grip of micro GT Survey 3 is the result of changes in tyre/surface contact. Chainage 60m onwards is in the racing line and subject to trafficking. Figure 6-12 shows the position of a F1 car on the racing line going over the asphalt concrete patch at Turn 14. This shows how the car is moving across the patch.

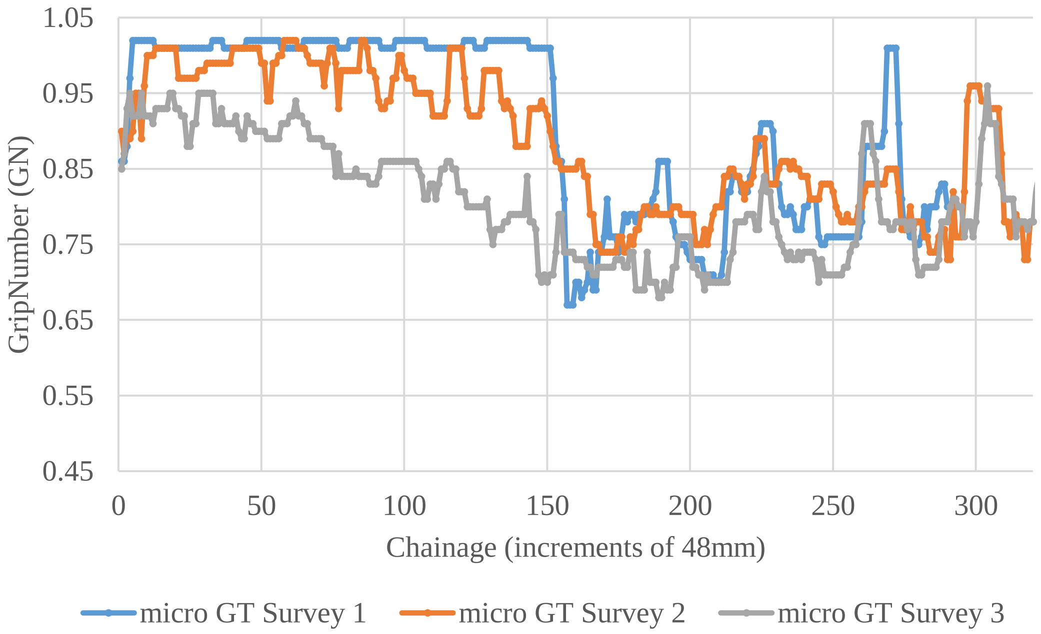


Figure 6-9 Lateral grip survey using the micro GripTester at Turn 14 Position C

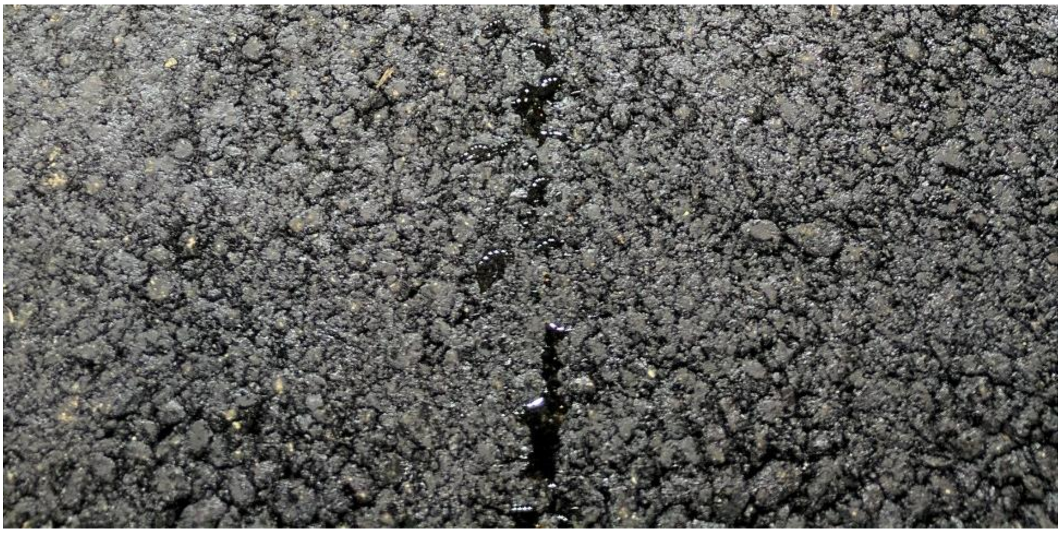


Figure 6-10 New asphalt concrete patch at Turn 14 showing water on the surface after wet grip testing

Figure 6-11 RoadGrip Trackblast high pressure water retexturing surface treatment

Figure 6-12 F1 car driving across new asphalt concrete patch

Figure 6-13 shows the evolution of grip at Position D. Figure 6-14 shows the evolution of grip at Position E. Figure 6-15 shows the evolution of grip at Position N. Comparison shows the influence of tyre/surface interaction and the development of the racing line. Less variation in lateral grip was observed at Location N in the braking zone at the approach to Turn 14 on the existing asphalt concrete. The spike at 241m occurs at the high friction edge line paint. A reduction in grip in micro GT Survey 3 is due to the high friction paint being worn off by tyre/surface contact.

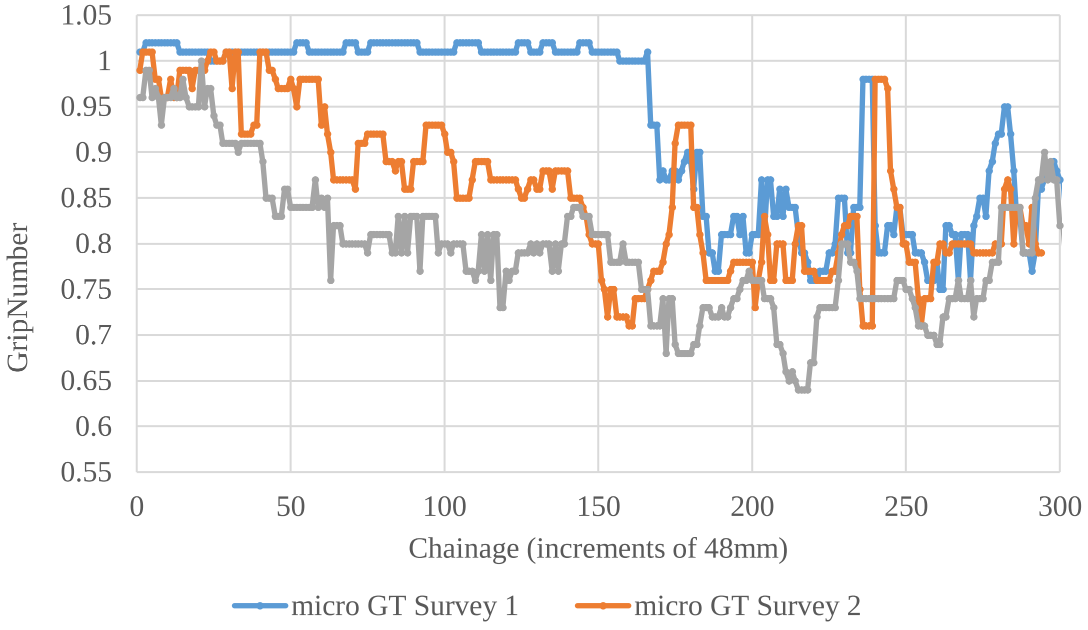


Figure 6-13 Position D at Turn 14

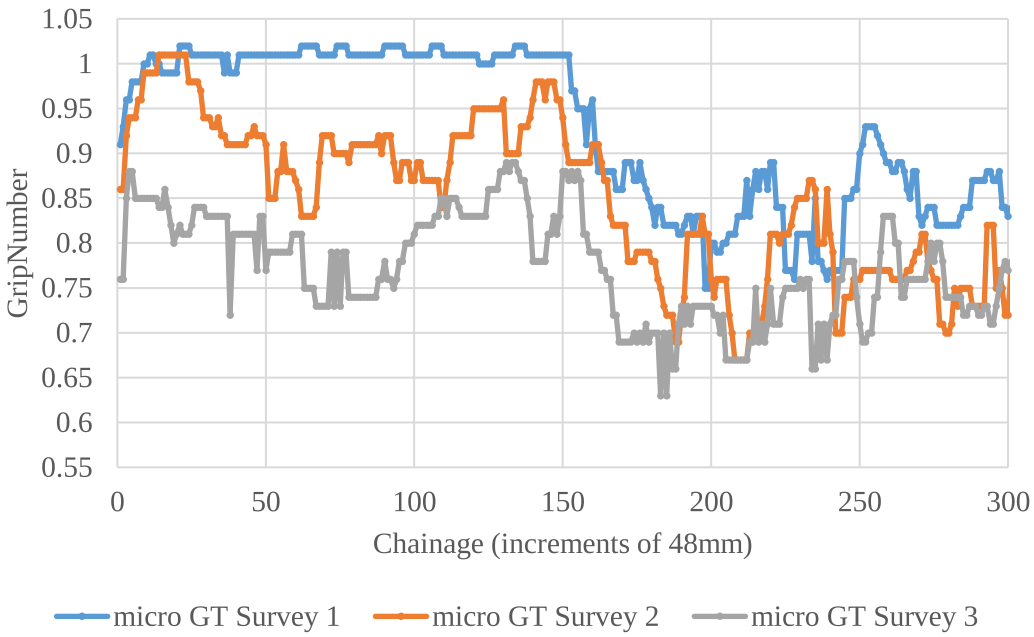


Figure 6-14 Position E at Turn 14

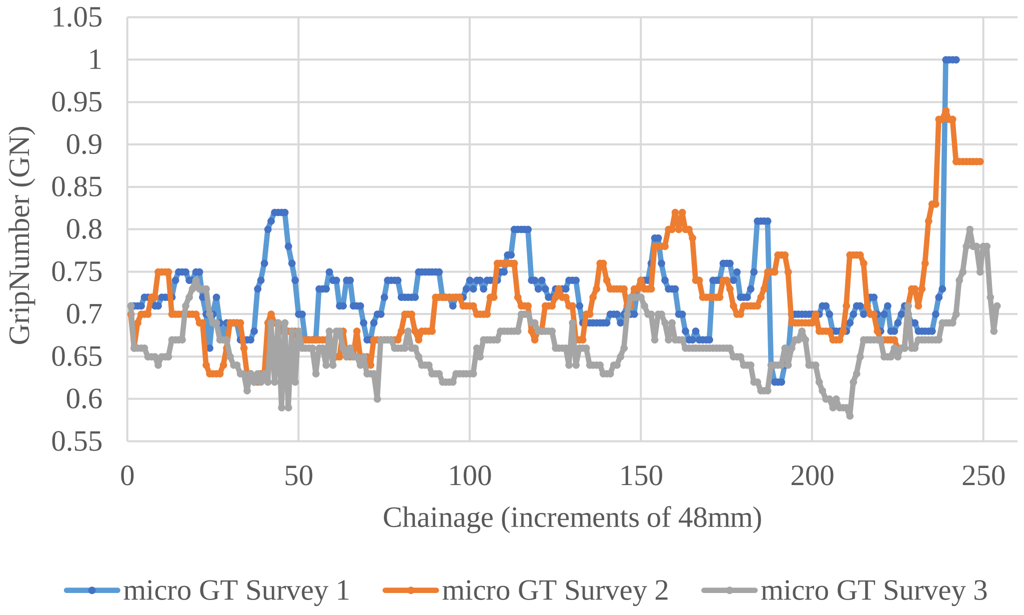


Figure 6-15 Position N Position N at Turn 14

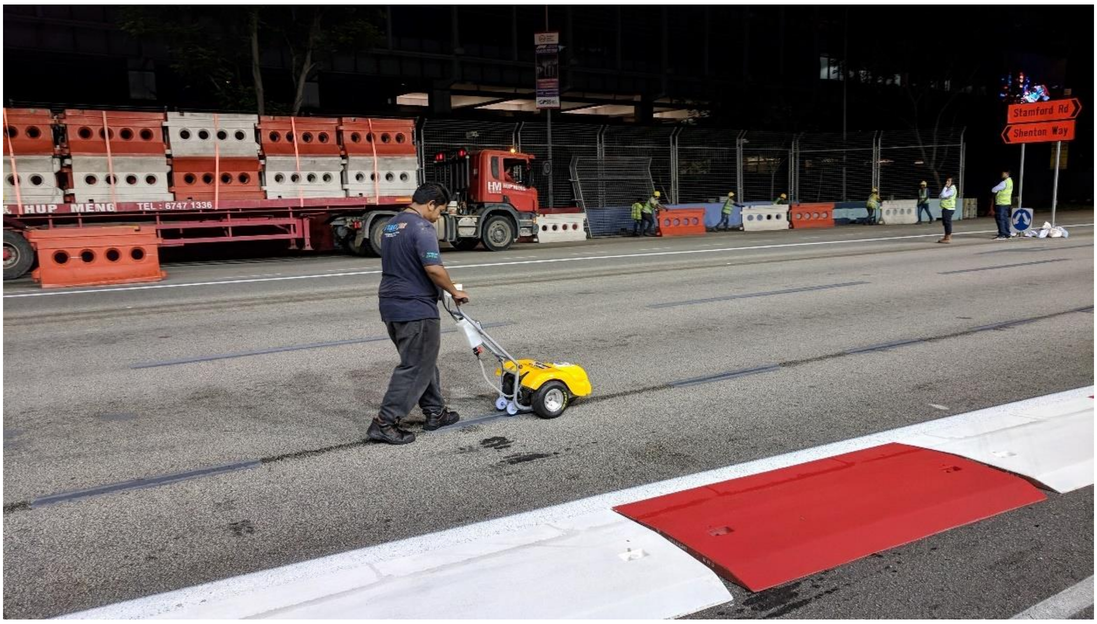


Figure 6-16 micro GripTester survey of high friction paint markings at Singapore Grand Prix 2018

Figure 6-16 shows a micro GripTester being used to measure the variation in grip between white lines that had been painted with high friction paint and the asphalt concrete road surface. The high friction paint is used to overcome the effect that the standard white highway markings might have on the tyre/surface interaction during the race. The results are plotted in Figure 6-17 . This shows a 0.5 GN difference between the road asphalt concrete and the high friction paint. The difference drops by 0.4 GN after 625m, where the standard white highway markings remained and had not been painted. This is a significant variation in grip.

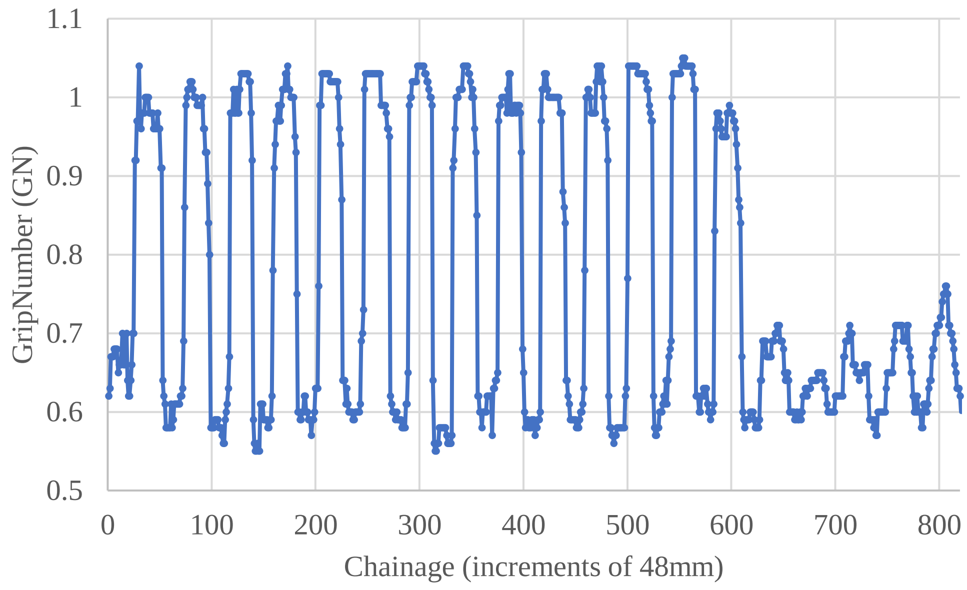


Figure 6-17 GN variation in white lines painted with high friction paint and asphalt concrete

The low speed micro GT data for each location were plotted in ArcMap to produce GripMaps. An example is shown in Figure 6-18. This shows a poorly defined racing line around Turn 14 and is due to the low accuracy of the 1 Hz GPS receiver used by the micro GripTester.

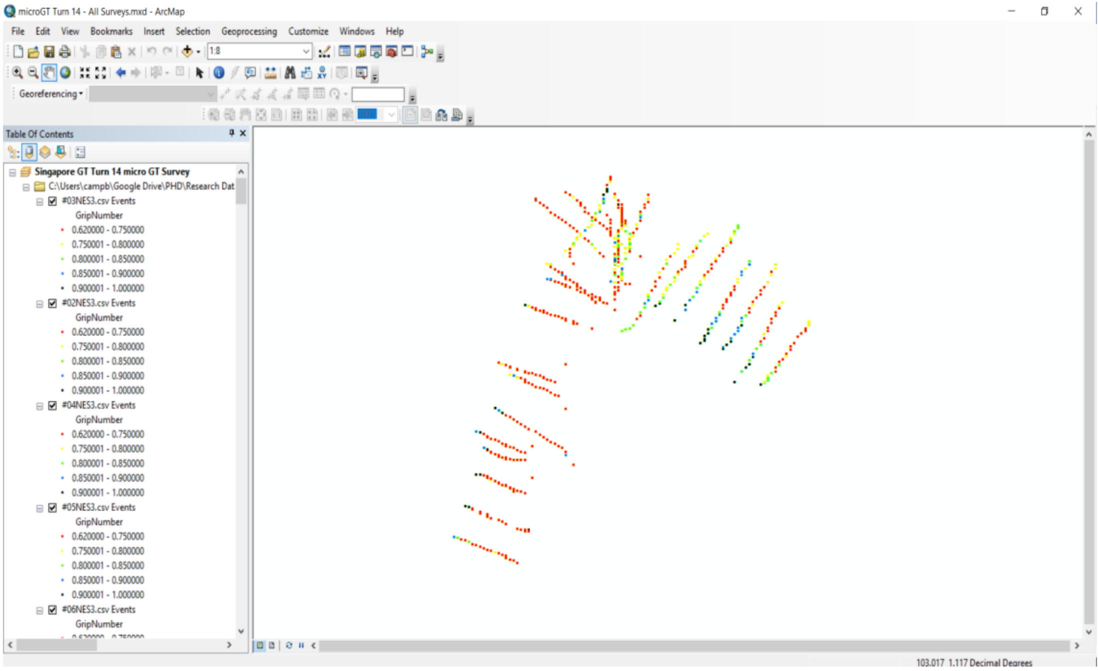


Figure 6-18 Example of a GripMap for lateral grip survey on ArcMap

CHAPTER 7

SURFACE TEXTURE AND GRIP MEASUREMENT

7 Chapter 7: 3D Surface Texture Modelling and Combining Grip Measuring Techniques

7.1 Introduction

This chapter evaluates texture related characteristics that may relate to grip. The methods used in this thesis to measure grip require access to the track that can be difficult, impractical or not allowed. Non-contact methods of texture measurement at differing macro and microscales offer an alternative to direct measurement in certain circumstances. Areal texture parameters could help better understand what may happen at the tyre/surface interface. Three examples are summarised in this chapter in order to illustrate how improvements to track surfaces from texture measurements may be achieved. The first example considers the starting grid box. The second considers how treatments such as high pressure washing or grinding influence grip. The final example considers tyre/surface enveloping phenomena.

7.2 Comparison of the (MTD) with surface parameters from CRP 3D models

Methods to measure macrotexture have been used in the road and airport industries for many years. Mean texture depth (MTD), measured using the Volumetric Patch Test (BS EN 13036-1, 2010) is considered the standard method to measure macrotexture. In recent years, F1 teams and tyre manufacturers have been observed using the Ames LTS laser scanner to measure surface texture. More recently use of the Alicona PortableRL microscope on track surfaces has been observed. There is little in the published literature as to how the data is used.

The CRP method as applied to highway surfacings was developed by Millar (2013) and McQuaid (2015) to offer an economic and straightforward method to generate 3D models of a surface from photographs. The process requires no specialised equipment, limited track time and is non-invasive. Three dimensional models can be produced quickly and analysed for a wide range of 2D and 3D areal parameters.

A comparison of MTD with surface parameters derived from CRP 3D models was carried out at Singapore Grand Prix 2018. Twenty-eight locations were selected with differing types of asphalt concrete, age and surface treatment work. This included the first six grid boxes on the starting grid. The starting grid was selected as macrotexture could play a significant role in car traction and ability to launch from a standing start.

In addition to images captured at each of the locations, the MTD at each location was estimated using the Volumetric Patch Technique (BS EN 13036-1:2010). A plot of MTD for each location is shown in Figure 7-1.

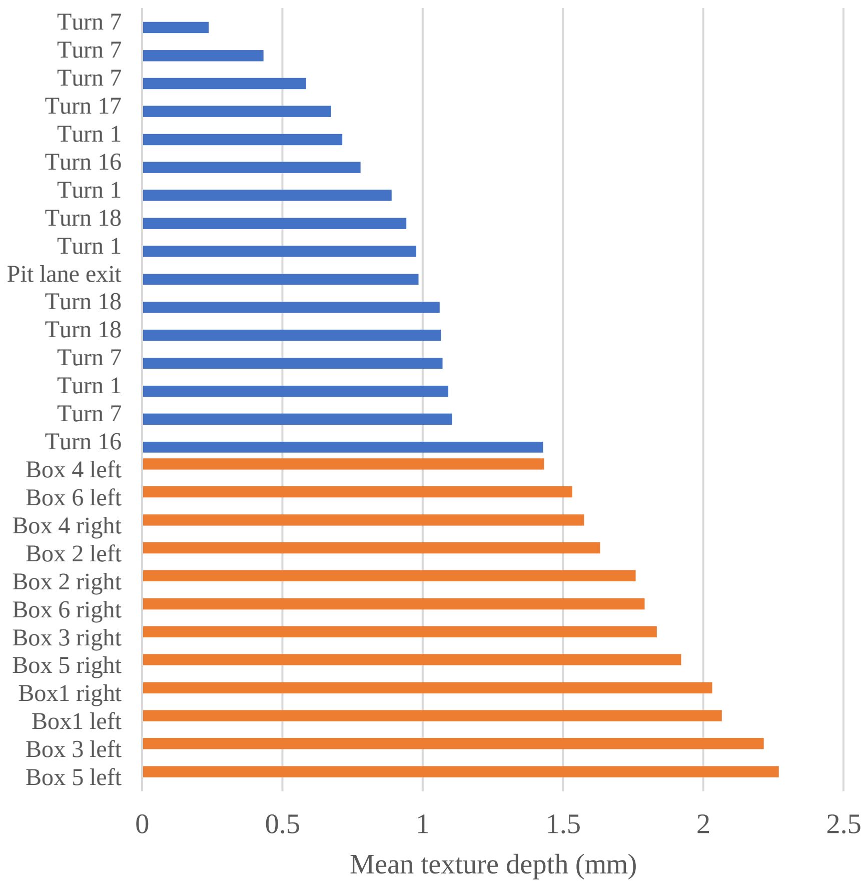


Figure 7-1 Plot of Mean Texture Depth for each location

The MTD varies from 0.24 mm at Turn 7 to 2.27 mm at the left rear axle position at starting grid box 5. Figure 7-1 shows two distinct groups of data. The lower texture values relate mostly to the street parts of the track. The lowest value at Turn 7 is attributed to an area of localised surface grinding carried out to address a surface anomaly. The area of low texture depth at Turn 7 may increase the risk of hydroplaning in a wet race. With one exception, the higher values, ranging from 1.43mm to 2.27mm, are located on the starting grid. Higher levels of texture at the starting grid suggests higher levels of traction than for other sections of the circuit.

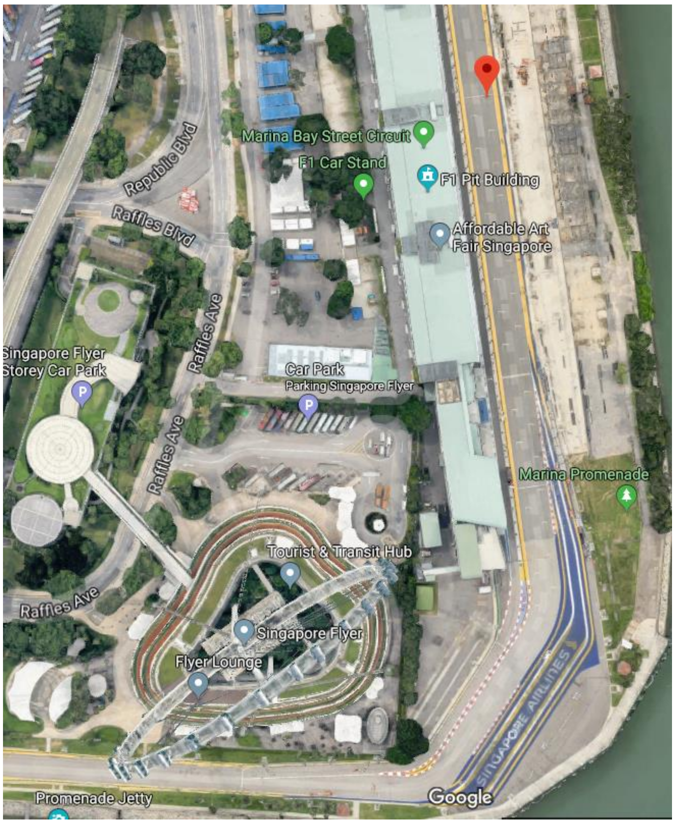


Figure 7-2 Google map showing position of the starting grid

The starting grid at the Marina Bay Street Circuit is shown in Figure 7-2. Grid boxes 2, 4 and 6 are located to the left, off the racing line, and consequently would receive less trafficking. Grid boxes 1, 3 and 5 are located in the racing line and are subject to increased tyre/surface interaction. The surface material for the starting grid is a positively textured mature asphalt concrete. After the first practice session there was some evidence of small aggregate particles breaking away from the surface.

Figure 7-3 shows a chassis template provided by the Renault F1 Team mechanics to select the correct position of the car rear axle in the grid box. This allowed accurate positioning of the CRP photographs and sand patch test with respect to the rear tyres of the car as shown in Figure 7-4. The MTD values for the rear tyre locations in each grid box are plotted in Figure 7-5.

This shows the MTD is consistently higher on the right side of the starting grid than on the left. The MTD under the right axle is consistently lower than under the left axle on the right side of the grid. The reverse is true on the left side of the grid where the texture depth under the right axle is consistently lower than under the left. The least variation in MTD between left and right axles is at grid box 1, followed by 2, 4 and 6. The highest variation is at grid positions 3 and 5.

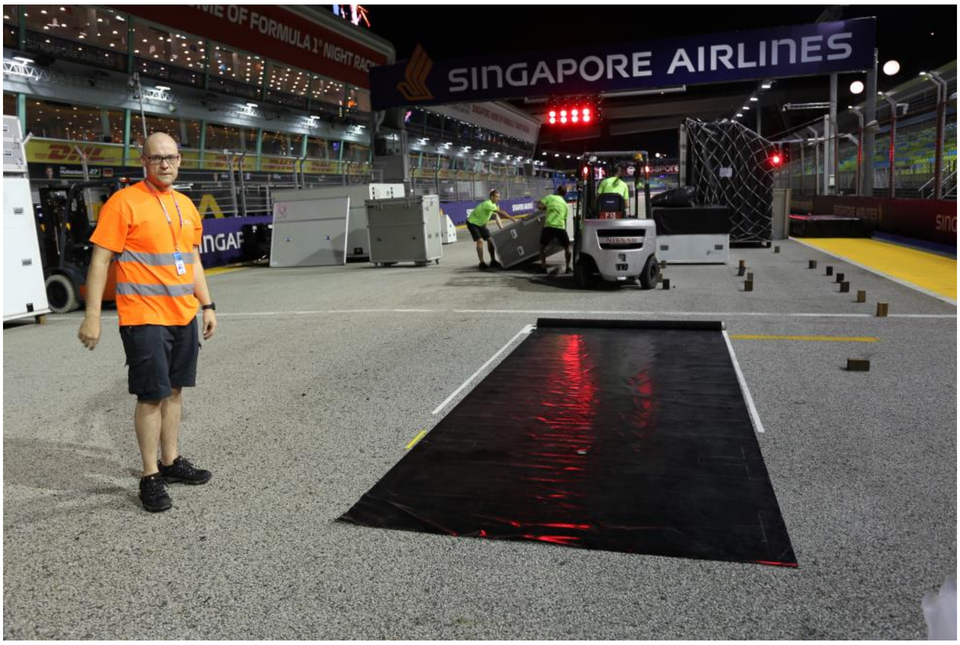


Figure 7-3 Chassis template used to locate car position within the grid box

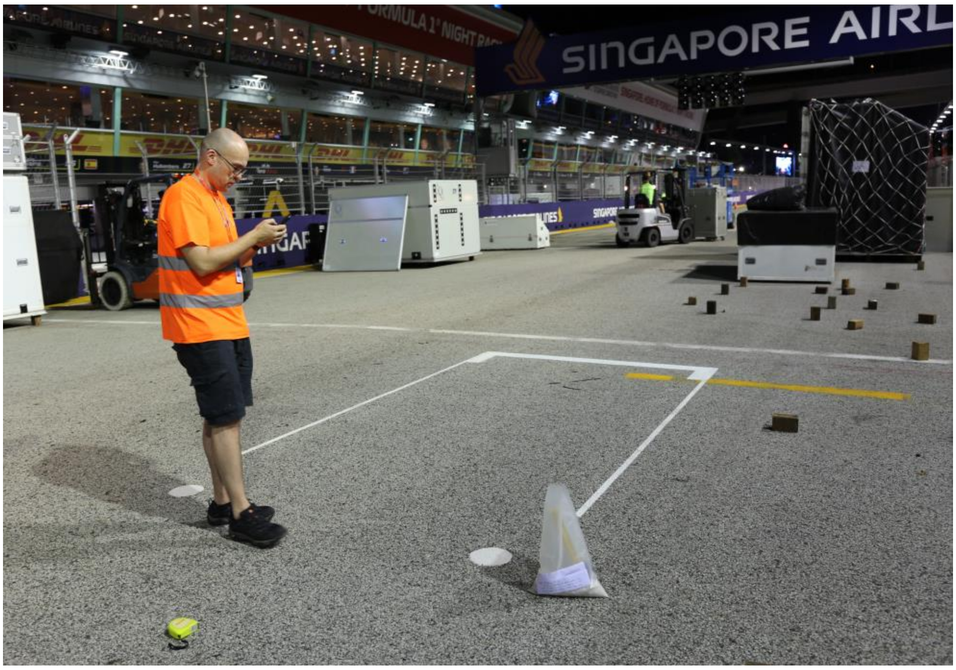


Figure 7-4 Positioning of sand patch tests

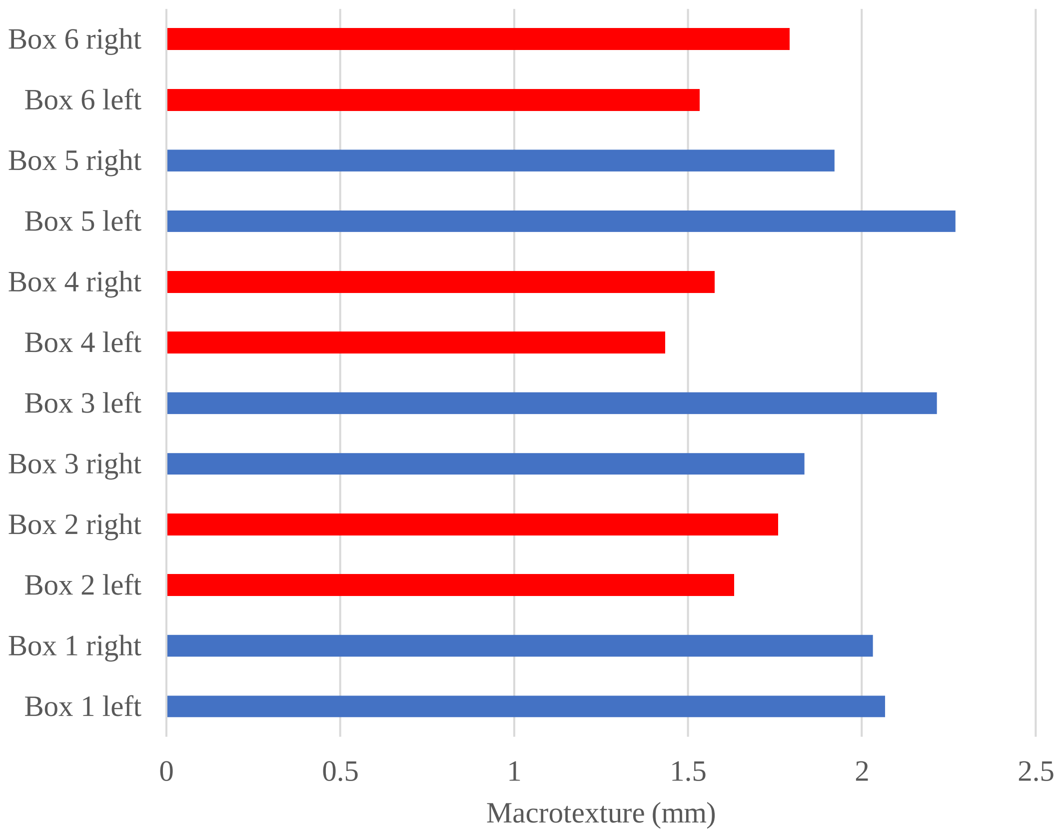


Figure 7-5 Plot of MTD values for the rear tyre locations in each grid box

The photographs taken at each grid box location were used to make CRP 3D models using Zephyr 3D Flow photogrammetric software. Models were then imported into Digital Surf MountainsMap surface analysis software for determination of areal parameters. Figure 7-6 shows a Zephyr 3D model from one of the grid boxes. Figure 7-7 shows a section of the model in Figure 7-6 at higher resolution showing recovery of surface texture in greater detail.

Surface areal parameters were extracted from the CRP 3D model exports. A comparison of MTD with the areal texture parameter Sp (maximum peak height) is shown in Figure 7-8. Sp was chosen as it represents the element of the texture immediately available to the tyre as the car starts to accelerate away from the grid box. This shows a coefficient of determination (R^2) of 0.62.

A similar comparison is shown in Figure 7-9 which plots data for all 28 locations chosen for MTD and CRP modelling. This shows the linear trendlines for both data sets to be closely aligned.

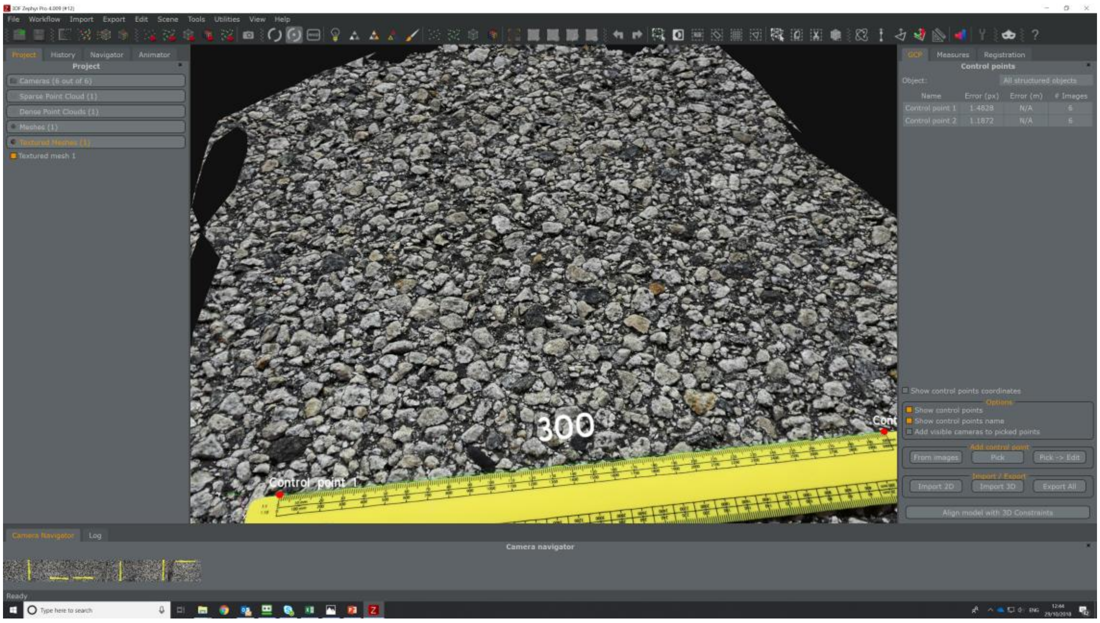


Figure 7-6 Zephyr 3D model from one of the grid boxes

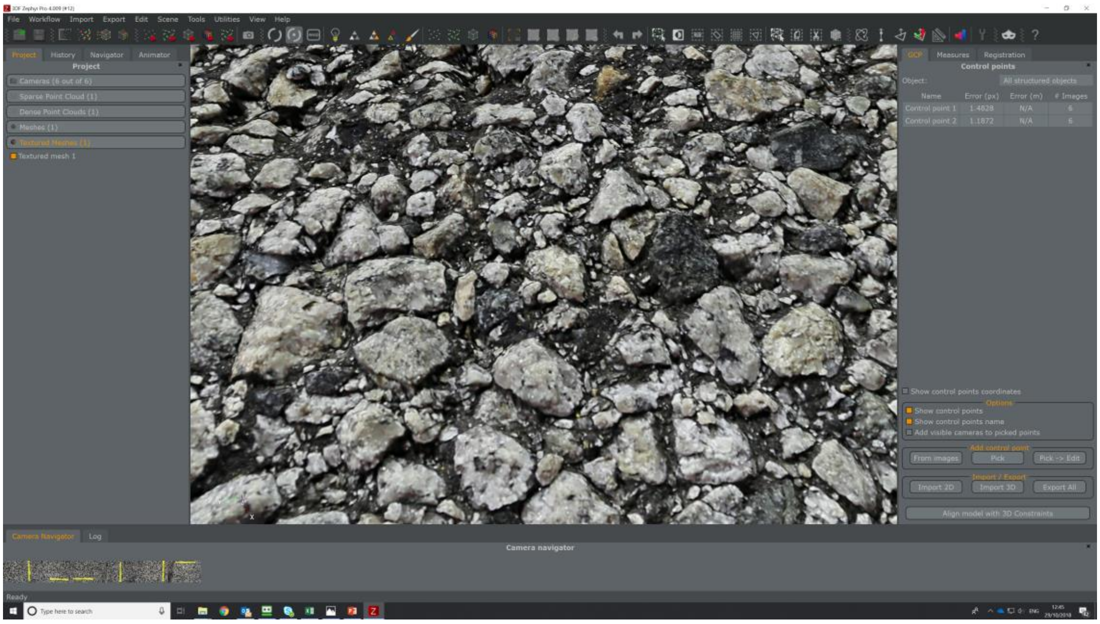


Figure 7-7 Section of the model in Figure 7-6 at higher resolution showing recovery of surface texture in greater detail

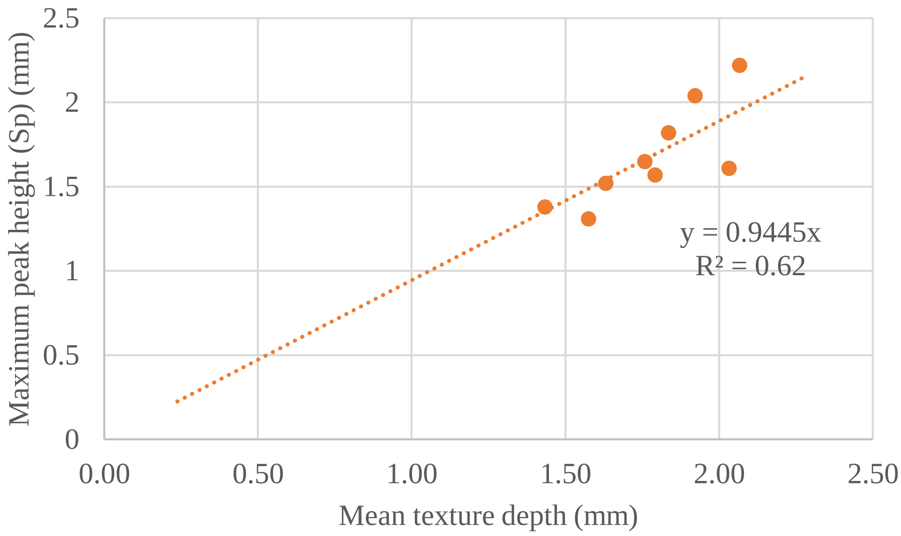


Figure 7-8 Comparison of MTD with Sp for grid box locations

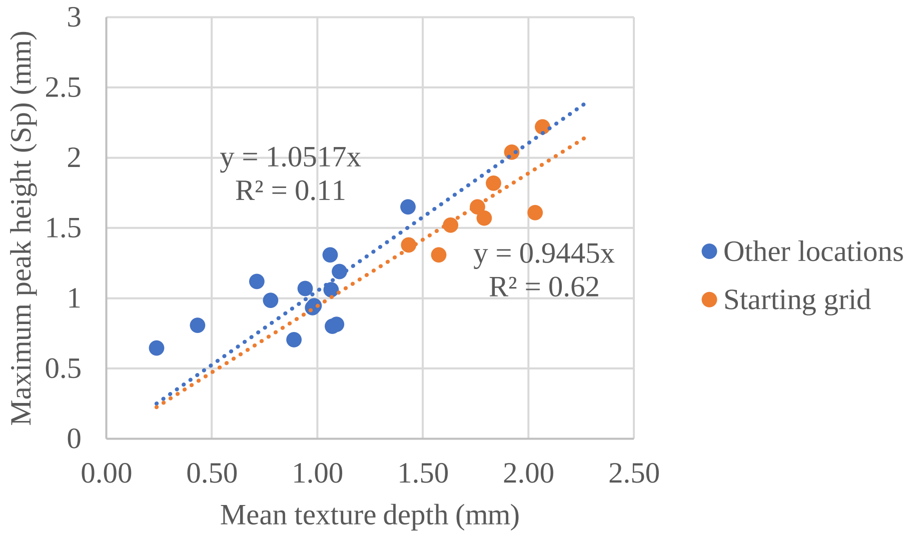


Figure 7-9 Comparison of MTD with Sp for all locations

7.3 Comparison of grid box MTD and Sp with GN

Grip data for grid boxes 1 to 6 was selected from the full GripMap survey recorded after qualifying as this would be representative of the track surface condition before the start of the race. The four laps that corresponded to the GripTester tyre passing over the car rear tyre position in each grid box was selected. Fifty meters of GripMap data from each lap was selected covering the six grid boxes. The 1m interval grip data is plotted in Figure 7-11 which also shows the location of each grid box. Also shown is the MTD of the foot-print where the car rear tyre would be positioned prior to the race start.

		0.69	0.72			0.64	0.61		Box 1
		0.69	0.76			0.6	0.62		
		0.66	0.75			0.62	0.6		Front
		0.69	0.73			0.6	0.57		
		0.68	0.73			0.63	0.61		
		0.66	0.72		2.1mm	0.63	0.61	2.1mm	Rear
		0.69	0.7			0.58	0.61		
Box 2		0.68	0.7			0.64	0.6		
		0.7	0.71			0.64	0.63		
Front		0.69	0.74			0.62	0.6		
		0.69	0.74			0.63	0.61		
		0.71	0.71			0.6	0.62		
Rear	1.7mm	0.71	0.72	1.8mm		0.6	0.59		
		0.7	0.71			0.63	0.63		
		0.71	0.7			0.66	0.65		
		0.73	0.71			0.63	0.63		Box 3
		0.68	0.74			0.63	0.66		
		0.67	0.7			0.66	0.62		Front
		0.69	0.73			0.62	0.61		
		0.68	0.73			0.62	0.63		
		0.69	0.7		2.2mm	0.66	0.61	1.9mm	Rear
		0.71	0.73			0.62	0.63		
		0.69	0.71			0.65	0.62		
Box 4		0.71	0.69			0.64	0.61		
		0.71	0.72			0.59	0.62		
Front		0.7	0.69			0.64	0.6		
		0.67	0.69			0.63	0.61		
		0.68	0.74			0.63	0.62		
Rear	1.4mm	0.67	0.68	1.6mm		0.64	0.61		
		0.67	0.73			0.65	0.61		
		0.68	0.74			0.62	0.61		
		0.67	0.71			0.67	0.59		Box 5
		0.66	0.72			0.67	0.63		
		0.7	0.75			0.67	0.63		Front
		0.68	0.74			0.63	0.6		
		0.7	0.75			0.66	0.61		
		0.71	0.75		2.3mm	0.65	0.62	2.0mm	Rear
		0.7	0.74			0.68	0.64		
		0.7	0.75			0.66	0.64		
Box 6		0.69	0.76			0.68	0.62		
		0.68	0.74			0.68	0.63		
Front		0.69	0.74			0.66	0.63		
		0.68	0.72			0.67	0.61		
		0.68	0.73			0.61	0.63		
Rear	1.5mm	0.71	0.74	1.8mm		0.65	0.58		
		0.72	0.73			0.63	0.62		
		0.73	0.74			0.62	0.63		
		0.73	0.74			0.63	0.6		
		0.72	0.7			0.64	0.6		
		0.74	0.71			0.65	0.62		
		0.75	0.68			0.67	0.6		

Figure 7-10 Conditionally formatted plot of GN and MTD at the rear tyre locations

The grip data shows the racing line side of the track; grid boxes 1, 3 and 5 to have lower GN. This difference is similar to the MTD analysis that shows the racing line side of the track to have higher texture. This illustrates how the asphalt concrete has responded to trafficking by the race cars in the racing corridor.

Figure 7-11 and Figure 7-12 plot GripNumber with MTD and Sp respectively. Time restraints resulted in only nine of the grid box data sets being analysed for Sp. In the legend RL denotes the right side of track, left rear wheel; RR denotes right side of track, right rear wheel, LL denotes left side of track, left rear wheel; LR denotes left side of track, right rear wheel. Both plots clearly show the difference in grip and texture parameters for either side of the track. The racing line has lower GN; and higher MTD and Sp. The same asphalt concrete in the track adjacent to the racing line has higher GN: and lower MTD and Sp.

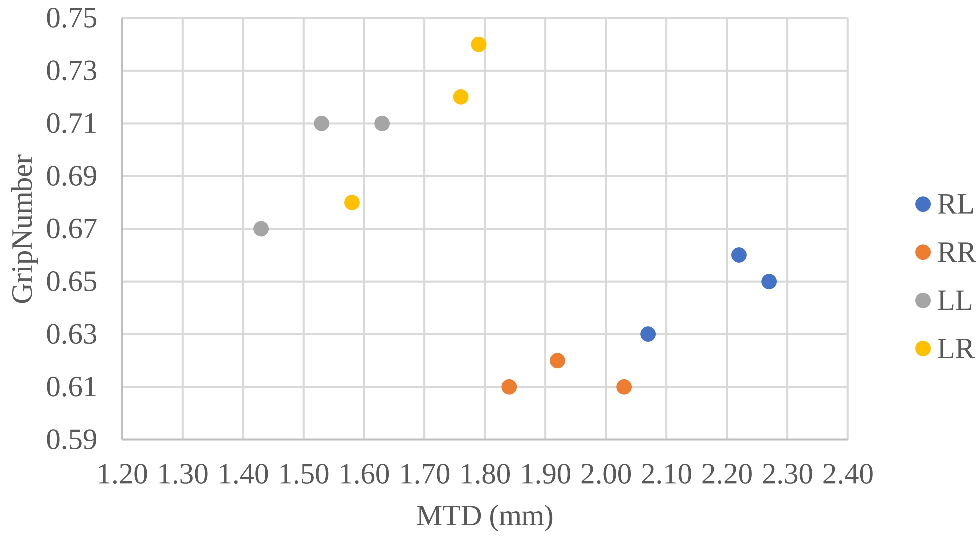


Figure 7-11 Plot of 1m interval grip data and MTD at rear tyre position

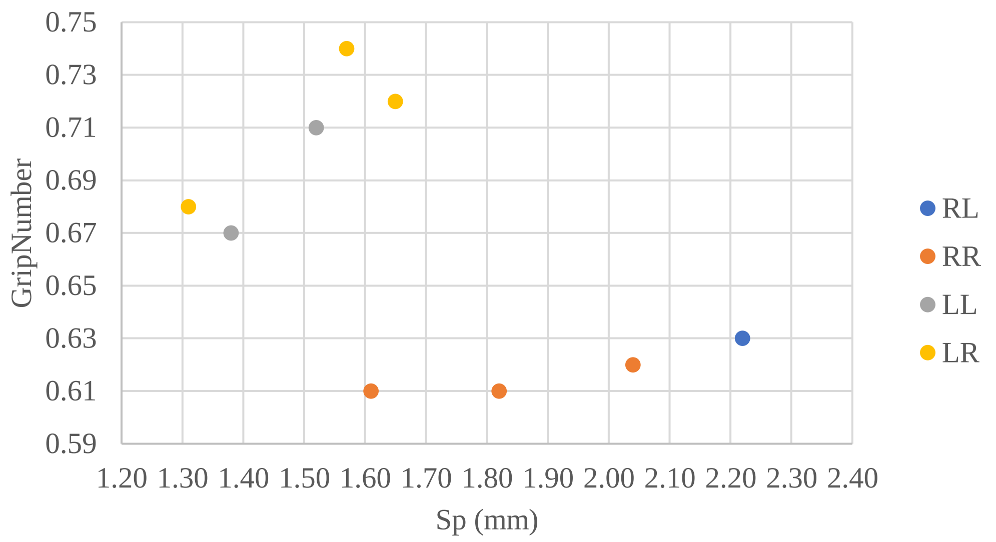


Figure 7-12 Plot of GripNumber and Sp

7.4 The effect of surface treatments on grip

The texture of a race track surface may need treated from time to time. For example, the joint between a patch with the existing surface may not be within tolerance. Heavy stresses associated with braking or cornering may cause the surface texture to decline. New patches of asphalt may need to have their surface coating of bitumen removed to improve levels of wet grip.

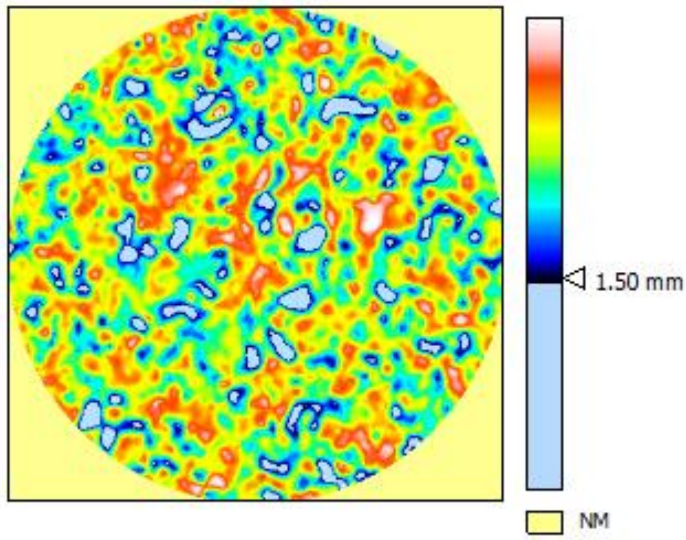
Mechanical grinding and two types of high-pressure water re-texturing were used at Singapore 2018 to address issues associated with surface texture. This example illustrates how MTD, areal parameters and grip data were affected at four locations in the racing line at Turn 7. The locations were (i) a patch of new asphalt concrete that was treated with high pressure water retexturing (ii) a new untreated asphalt concrete (iii) a mature untreated asphalt concrete and (iv) a section of the mature asphalt concrete that had been subjected to mechanical grinding to level a joint with the new patch.

Two estimations of MTD for the mechanically ground asphalt concrete gave 0.24mm and 0.43mm. Figure 7-13 shows a 520 mm diameter sand patch for the ground asphalt surface. Analysis of the 3D models for the ground asphalt concrete shown in

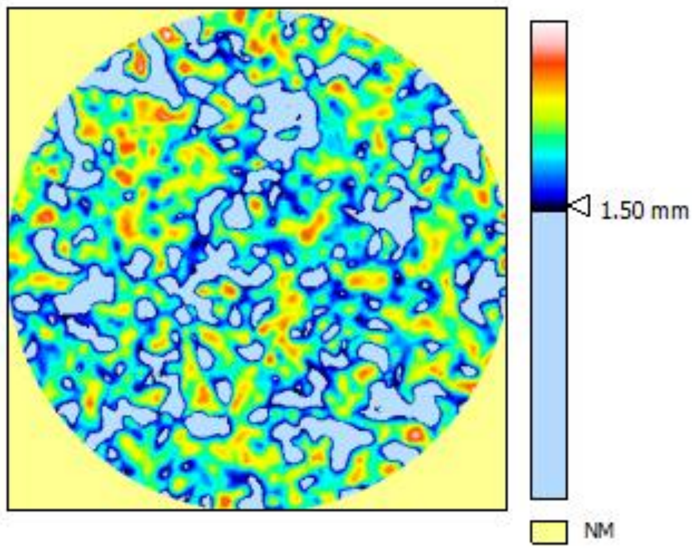
Figure 7-13 showed a texture depth ranging from approximately 1.2 mm from the highest peak to the lowest valley of the surface. The analysis found that only 2.16 % of the surface texture was below a depth of 1 mm.

Figure 7-13 A 520 mm diameter sand patch for the mechanically ground mature asphalt concrete at Turn 7

The MTD for the treated and untreated areas of Turn 7 was marginal with 1.07 mm and 1.11 mm respectively. The untreated asphalt concrete had a maximum texture depth of 3.8 mm compared to 2.7 mm for the treated sample. The definition of peaks to lower valleys was better showing the benefit of removing excess bitumen by the high-pressure water treatment. This is illustrated using Island Analysis as shown in Figure 7-14 for the treated and untreated surface within the new patch. This shows that the high-pressure water treatment has reduced the datum therefore, relatively the high points are more defined. This can be seen in Figure 7-14 (b) where a greater area is shown to be below the 1.5mm planar. This is a result of the treatment increasing the macrotexture.



(a)



(b)

Figure 7-14 Island analysis showing apparent contact area at for the new asphalt concrete at 1.5 mm depth for high water pressure treatment (a) and untreated (b)

Figure 7-15 micro GripTester water testing at Turn 7

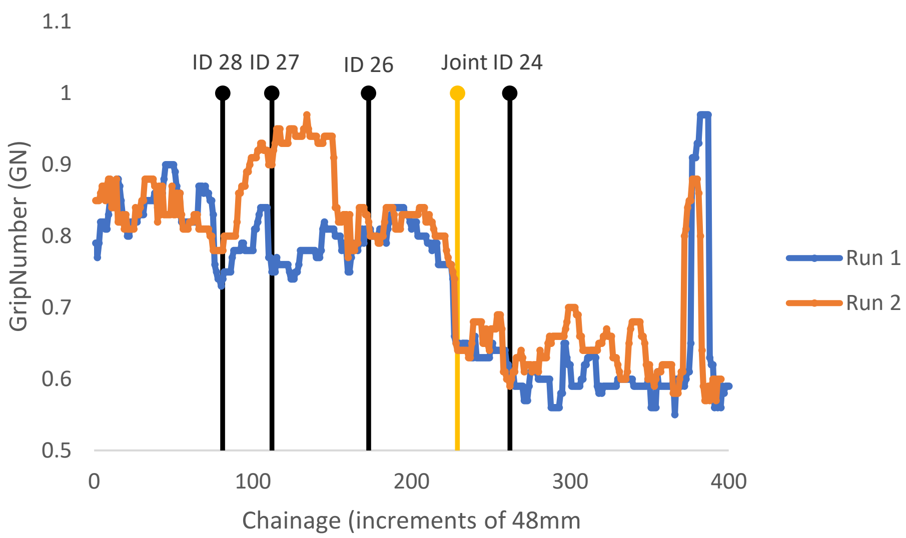


Figure 7-16 Turn 7 wet grip survey results

The water trails from 2 micro GripTester surveys are shown in Figure 7-15. Figure 7-16 shows the results of these grip tests. They each start on the old asphalt concrete, move onto the new asphalt concrete patch and traverse the joint onto the old asphalt concrete that has been subject mechanical grinding. The spike at the end of each run highlights the grey coloured high friction paint. The Event Marker button on the micro GripTester was used to mark the relative position of these different surface sections. These positions have been marked with the corresponding site location ID number on the plot. The joint that has been levelled with mechanical grinding is also marked. Run 1 and Run 2 show a similar pattern with the exception of one area at chainage 89m to 156m. Table 7 shows the GN and MTD for the four locations. The new asphalt patch in Run 1 had not been treated. In Run 2 the new asphalt patch had been treated using high-pressure water and showed higher wet grip. Despite the very low MTD of the two locations there is still reasonable GN, suggesting that there may be a resulting micro scale of texture that influences wet grip.

Table 7 micro GripTester GN and MTD data

Site ID	Run 1 (GN)	Run 2 (GN)	MTD (mm)
ID 24	0.61	0.59	0.24
ID 26	0.81	0.83	0.43
ID 27	0.77	0.9	1.07
ID 28	0.73	0.78	1.11

7.5 Tyre/surface enveloping

The red paint markings at the edge of Turn 3 exit and shown in Figure 7-17 are an example of how rubber deposits resulting from high stress at the tyre/surface interface. In order to achieve the fastest route around Turn 3, the cars were running over the line towards the barrier.

High friction red paint is applied directly onto the asphalt concrete before the start of the race weekend. The paint is assumed to be evenly applied across the surface.

The black deposits visible on the surface of the newly painted surface are assumed to be mostly rubber from the tyre. The black deposits show the accumulation of contact points generated at this high stress tyre/surface interface. These black deposits facilitate investigation of the phenomenon of enveloping.

Figure 7-17 Black deposits on high friction paint at Turn 3

Figure 7-18 3D model showing rubber deposits on a red line marking at Turn 3

Figure 7-18 shows a Zephyr 3D model of the black deposits at Turn 3. This shows black deposits associated with the higher parts of the painted textured surface. Figure 7-19 is a MountainsMap image showing the maximum depth into the asphalt concrete is around 5.2 mm.

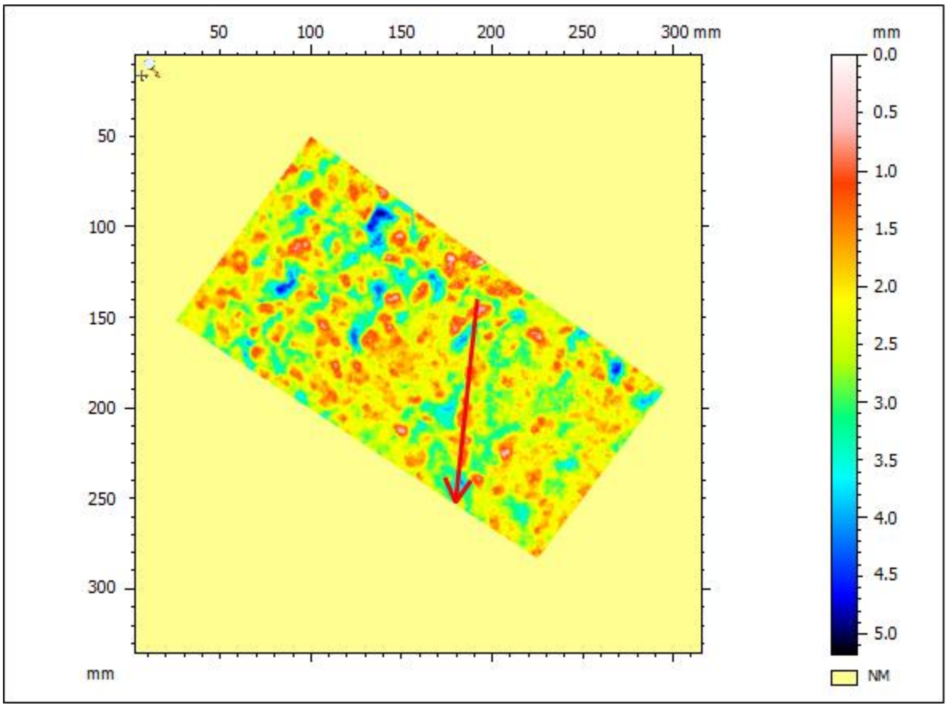


Figure 7-19 MountainsMap model of Turn 3 asphalt concrete texture

2D Profiles were extracted from the 3D model. The red arrow in Figure 7-19 delineates the section profiled in Figure 7-20. There are 2 parts of the profile dropping to a depth of approximately 3 mm from the highest point of the profile. If this profile is compared against the 3D Zephyr model shown in Figure 7-18 it appears that the depth of enveloping is approximately 1mm.

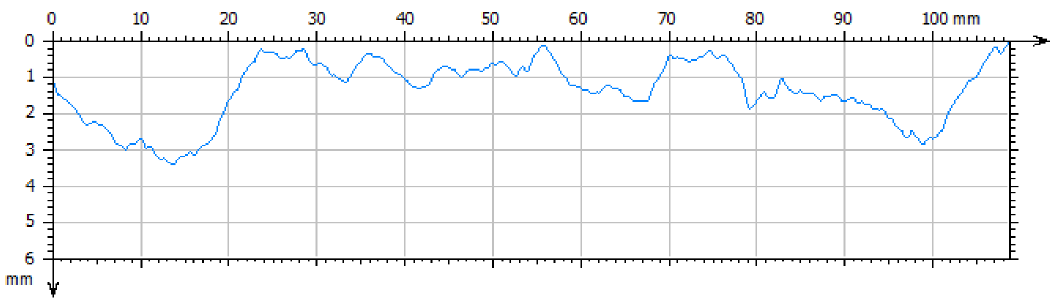
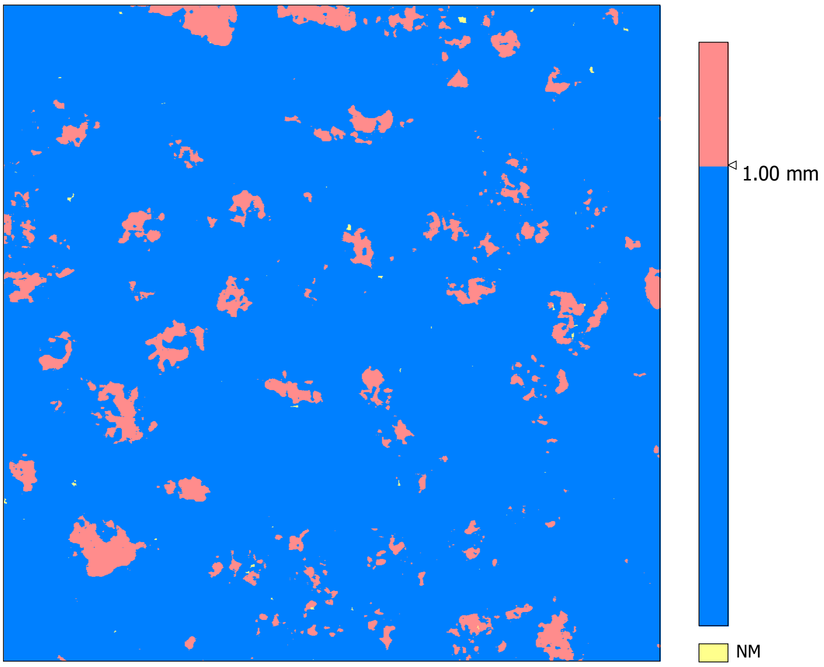


Figure 7-20 2D profile of the painted asphalt concrete

The depth of the tyre/surface interface can be further investigated using a slices study. This determines the change in volume and area parameters to be determined with increasing depth into the texture of the asphalt concrete surface. Figure 7-21 shows a slices study showing volume and area parameters at a depth of 1mm into the surface texture of the asphalt concrete. This shows that the projected area above 1mm is just 7%. The distribution of contact areas above 1mm are similar to the deposit shown in Figure 7-20.

It is not known what loading the car tyres are experiencing as it goes around Turn 7. Using the rubber deposits as evidence of where contact is taking place then the 3D model analysis suggests that only a small area of the asphalt texture is contacting the tyre.



Parameters	Unit		
Projected area	%	93.2	6.79

Figure 7-21 Slice analysis from Zephyr model

CHAPTER 8

DISCUSSION

8 Chapter 8: Discussions

8.1 Introduction

This Chapter discusses the main findings and results from this thesis. Key ideas and learnings from meetings with motorsport governing bodies, commercial rights holders and figureheads have been considered. It will follow the project from the initial stages at Yas Marina Circuit through the testing of methods at Knockhill Racing Circuit to applying and expanding the system to racing events including Formula 1 at the Singapore Grand Prix. This is the culmination of five years research that commenced at Yas Marina Circuit, Abu Dhabi. Considerable effort has been expended in accessing racing circuits and the secretive world of professional motorsport.

Throughout the research, multiple GripMap surveys have been completed extending from approximately 2,000 to approximately 40,000 data points. Other tests such as the Volumetric Patch Technique, 3D surface modelling and the measurement of lateral grip have been utilised to better understand racetrack grip and surface characteristics. The data has been analysed in different ways to identify, quantify and understand racetrack surface behaviour.

Throughout the course of this research, the methods have been refined through testing and developments in software, processes and procedures. The methods presented and implemented in this thesis are new to motorsport. Mapping of a racetrack surfaces through live professional motorsport events has never been carried out before and this thesis represents a substantial and unique contribution to knowledge therefore. The following discussions are aligned with the objectives of the thesis presented in Chapter 1.

8.2 Critically appraise the literature and ascertain the perspectives of motorsport governing bodies and stakeholders to identify knowledge gaps

A critical literature review is presented in Chapter 2 which identified knowledge gaps in the following areas:

- Frictional properties of tyre rubber and its interaction with race track surfacing are complex and not fully understood.
- There is no accepted unified theory of rubber friction in the context of race track surfacings.
- The relationship between a tyre and an imperfect surface, a phenomenon known as enveloping, is not yet fully understood.
- The influence of racetrack construction materials and surface characteristics on high-speed tyre interaction is not yet understood.
- Impact of early life skid resistance phenomena on racetracks and race vehicles.
- Effect of surface treatments such as high pressure water retexturing on racetrack grip.
- No standardised method for measuring racetrack grip exists.
- There is no published research on the evolution of surface grip for racing circuits.
- How do motorsport teams quantify grip and what do they do with grip data?
- The effect of environmental conditions such as rain on grip on race tracks is unknown.
- No FIA or mandatory standards for surface materials or surface testing exist.

It was established that no significant published research on the topic of racetrack grip measurement is available. There was no evidence of surface approval testing techniques for race tracks. The review found a small number of articles related to race track construction and the surface materials used. This information from trade press, suggested that the material and construction techniques used on racetracks are similar to those employed in the road industry. The transfer of knowledge and concepts into a motorsport/racetrack environment is applicable because the surfaces are constructed with similar materials.

The literature suggests a consensus that the adhesion component of friction arises from the softer rubber molecules becoming thermally energised thus creating a stick/slip reaction from tyre/surface contact. Adhesion is thought to be more associated with interaction with the surface microtexture. Bulk hysteresis loss is the loss of energy from the tyre deforming and reforming around the surface macrotexture or roughness. The reaction generates heat from lateral tyre movement and is associated with tyre degradation. This is particularly relevant to motorsport as the race tyres are designed to be thermally sensitive. Performance of race tyres underpins the vehicle setup.

Many terms are used to describe the interaction of a surface with a tyre. Skid resistance is the term common to highway and airport surfaces. However, the term *grip* is most often used in motorsport. For that reason, the term *grip* was adopted for this thesis.

The importance of texture related characteristics of a road or runway pavement and the underlying materials is established in literature. The tyre grip of a vehicle is highly dependent on the surface. Six important surface features that influence the tyre/surface interface are: aggregates, bitumen, void content, paving/compaction, texture and type of material. The influence of these surface characteristics when transferred to the extreme forces generated in motorsport is unknown.

The measurement of grip and surface characteristics on roads and airports dates back to the 1930s. A large number of testing methods exist. Devices for measuring skid resistance fall into three main categories: static, transverse and longitudinal. The literature review found that of these, the fixed slip-ratio CFME is the most applicable to motorsport. Woodward et al., (2012) used fixed slip-ratio CFME to measure grip at Yas Marina, Abu Dhabi. Evidence has been presented of a push fixed slip-ratio CFME being used by teams in Formula E and WRX to measure localised race track phenomena. The micro GripTester was first adopted by a Formula E team and subsequently by a WRX team after it was observed seen being used at the Singapore Grand Prix 2017 as part of this research.

Millar (2013) developed a 3D modelling method using CRP to model surface texture and grip at the same circuit. Examples of 2D laser texture devices being used on racetracks by the F1 tyre supplier and F1 teams was highlighted. How the data generated by the 2D devices unknown.

It was discovered that the FIA is planning to develop a homogenised approached to racetrack surfaces. This will include creating standards on materials and testing. It was suggested that this is to be considered over the next five to ten years.

8.3 Evaluate and select appropriate resources

An evaluation of existing testing methodologies that are accepted for use on roads and airports was undertaken. Literature from previous studies and harmonisation projects such as TYROSAFE (2010), NCHRP (2019) and ROSANNE (2019) were used to identify and evaluate testing methods. A review and evaluation of the equipment having potential for assessing racetrack grip is presented Chapter 3.

The British Pendulum Tester (BPT) (BS 7976-2, 2002) was highlighted by the TYROSAFE (2010) project as being the most prolifically used device for measuring grip. The literature review demonstrated a large volume of work detailing the historic significance of the BPT as setting the original baseline technique for measuring grip. Recent studies have been undertaken by Ciaraviola et al., (2017) which adapt the technique to test rubber/surface interaction with greater relevance for tyre manufacturers. The limitation of the BPT device is that it is a spot test and achieving a representative sample of a complete racetrack would be difficult and time consuming.

The Sideways-force Coefficient Routine Investigation Machine (BS 7941-1, 2006) is the most commonly used method of measuring the grip of the road network in Europe. It has a sideways or transverse measuring methodology utilising a measuring wheel originally based on a motorcycle wheel angled onto the surface.

Although the device is widely used it is mounted on a HGV chassis. The large size of the device makes it impractical when negotiating the tight geometry of a racetrack.

The GripTester (BS 7941-2, 2000) was found to be the second most used CFME used in Europe on roads. The device also has a long history of use on airports. Using a fixed slip-ratio methodology which is similar to that of antilock braking, the trailer-based device was first used to measure grip on a race track in 2007. It is relatively portable and does not require a special tow vehicle. The GripTester has subsequently been used to measure a large number of tracks in the United Kingdom, mainland Europe and overseas. GripTester data is measured along with GPS coordinates every 1 m increments. The data is output in a CSV format that can be imported into third party software packages for data analysis. The slick measuring tyre is sensitive to changes in grip associated with track surfaces.

The micro GripTester (micro GT) is now being used by teams for the local measurement of race track grip. This is a smaller push version of the trailer-based GripTester and is based on the same principle and using the same measuring tyre. The micro GT device can be packed into a portable flight case that is easy to transport. Data can be collected and analysed quickly. It is not known how this data is used by the motorsport teams.

Methods that quantify surface texture were considered. The baseline texture standard volumetric patch test is quick and straightforward to carry out. However, in terms of better understanding the role of track surface texture it only gives an estimation of Mean Texture Depth (MTD) of a surface at a macro scale. Profiling systems based on 2D and 3D lasers such as the Ames device were considered. This device and similar from other manufacturers are known to be used by F1 tyre suppliers to evaluate racetrack surface grip.

The data gathered from the Ames device is used to select the tyre compounds to be used at F1 races. A number of F1 teams also use this device. How they analyse and apply the data is not unknown. The device has the ability to calculate Mean Profile Depth (MPD), Texture Profile Index (TPI), Estimated Texture Depth (ETD), Root

Mean Squared (RMS), Ra, Rq, Skewness, Kurtosis and VAR. A typical scan area is 107.95mm x 72.01mm.

3D modelling of a surface using the CRP method was evaluated. CRP is a non-invasive image based approach. Advancements in mobile phone camera lenses mean that they can now be used to generate 3D surface models for analysis. Many types of 2D and 3D areal surface parameters can be derived from these surface models at both micro and macro texture scales. The efficiency with which models can be processed and analysed makes the CRP method an attractive approach to help explain the contribution role of surface characteristics to grip variation.

It was established form motorsport stakeholders that a fuller understanding of racetrack surface grip is required. Table 2 compared the needs of stakeholders with what they currently do to measure racetrack surface grip. Chapter 3 considered the accepted methods of measuring grip commonly used in roads and airports. Table 2 is a decision-making matrix that indicated the GripTester was the most suitable device for full track grip measurements. The micro GripTester was identified for focused grip surveys. While the volumetric patch test and CRP were selected for evaluating racetrack surface texture and analysing 3D surface models respectively.

8.4 Design a test method to measure race track grip

This thesis has detailed development of a test method to measure grip called the GripMap Method (GMM). This is a standardised method that is used to measure the variation in both longitudinal and lateral grip for an entire track surface. This identifies what has been termed the GripMap Corridor (GMC) for a track. This corridor roughly corresponds to the racing line. Most variation in grip occurs within this corridor. The key components considered in development of the GMM are discussed in the following section.

8.4.1 Test speed

A review of literature found that the effect of speed on testing roads and airports is well researched. This has resulted in the standardised test speeds for use on roads of

50 km/h and between 65 km/h and 95 km/h on airports. Experiments at Knockhill Racing Circuit found it was possible to achieve a consistent speed of 30 km/h around the racetrack. Constant speeds of 50km/h and 80km/h were difficult to maintain due to the sudden variation in elevation and track geometry at tight corners. Testing at Yas Marina Circuit, Abu Dhabi resulted in an accidental toppling of the device on the hairpin at Turn 7.

The standard road-testing speed of 50 km/h was deemed too fast. The slower speed of 30 km/h was considered acceptable for safe use on racetracks without compromising grip data quality. Experiments with cruise control showed a more consistent speed could be achieved. However, care is required were there are large changes in track elevation to ensure that cruise control does not deactivate.

A standardised method of testing grip based on data collected at 30 km/h has raised concerns within motorsport. Figure 4-4 illustrates the results of the racing line speed trials at Knockhill. The effect of increasing speed causing a decrease in measured grip is shown. This agrees with Nursetiawan (2008) for different road surface materials. To counter motorsport concerns over slow speed testing, a power relationship with a R^2 value approaching 1.0 has been found for GripTester data measured at speeds from 4 km/h to 80 km/h. Using this model the grip data can be extrapolated to 250 km/h which was selected as it is considered high speed for most motorsport categories. The extent to which this is valid is unknown at the moment and its measurement is outside the limits of this thesis.

8.4.2 Wet or dry testing

The majority of top-level motorsport events take place in dry conditions. Racing in wet conditions increases the likelihood of aquaplaning or wet skidding accidents. There are also issues with visibility at high speeds due to splash and spray. Recent high-profile incidents around events being cancelled due to water on recently surfaced tracks and concerns over safety suggest a need for wet grip testing.

Literature shows that testing in dry conditions produces high levels of measured grip data for almost all types of road surfacing material and the different aggregates used.

Wetting the surface shows much greater differentiation between the aggregates used and the types of asphalt mix. Road and runway grip is always tested wet using a controlled water film thickness. A water film thickness of 0.25 mm is standard for measuring grip on roads. A 1mm water film thickness is commonly used for testing airports. Nursetiawan (2008) found that wet GripTester values did not vary significantly between 0.25mm and 1mm water film thickness for a range of road surfaces.

Once a surface is wet its dry grip value will decrease. A water film thickness of 0.25mm is recommended when carrying out a GMM of the entire track surface. Application of a water film thickness of 0.25mm reduces measuring tyre wear and optimises the amount of water carried in the water tank.

8.4.3 The full racetrack grip survey procedure (GMM)

A test method for a full grip survey of a racetrack was detailed in Chapter 4. A list of the required equipment was outlined detailing the hardware and software required. A consistent test speed of 30 km/h and water film thickness of 0.25mm has been recommended. The survey procedure consists of starting at the outer left-hand edge of the track limit. After a full lap of the edge line the tow vehicle moves one meter over to the right. A second full lap is completed using the water trail of the first lap as a guide. On completion, a third lap is completed one meter to the right. This continues until the right edge line of the track is reached.

This will produce a dataset of between 5000 and 80,000 unique grip data points depending on the circuit or element of the circuit being surveyed. This covers the entire track surface with a nominal 1m x 1m grid of data points. Features such as the racing corridor, racing line, grip variation, grip evolution and different surface materials can be visualised when the data is plotted to produce a GripMap.

8.4.4 Analysing the grip data

Methods to analyse racetrack grip survey data were proposed in Chapter 5. Statistical representation of the large grip data sets was considered. The cumulative frequency analysis method is presented as a preferred option. Methods of visualising the grip data as a GripMap using colour-banded thresholds are discussed. Simple GripMaps can be generated using Excel. The preferred method is to use GIS software such as the Esri ArcGIS suite. The features and tools of ArcMap software were shown to allow the GripMap data to be interrogated and queried allowing a more detailed analysis. The georeferenced data can be spatially aligned with other datasets such as vehicle data. These features increase the scope for developments in analyses techniques to better understand racetrack grip.

8.5 Apply the test method to the motorsport environment

The GripMap Method (GMM) has been used to evaluate a wide range of motorsport circuits in the UK, mainland Europe and overseas. Due to commercial restraints, the data examples from just three circuits have been presented in this thesis. The circuits were Knockhill Racing Circuit, Scotland; Yas Marina, Abu Dhabi and the Marina Bay Street Circuit, Singapore. These examples help illustrate how the GMM test method can be used to show how the track is influenced by a motorsport event.

8.5.1 British Touring Car Championship 2015 Knockhill event

The GMM test method was used to evaluate variation of racetrack grip before and after the BTCC 2015 Knockhill event. This found the mean wet grip value for the entire track to decrease over the event. This is visible in Figure 5-17, Figure 5-18, and Figure 5-19. The areas that are most prone to heavy tyre/surface interaction such as braking zones, corner apexes and acceleration zones are more pronounced in the GripMap recorded after the BTCC event.

This reduction in measured wet grip is attributed to the intensive tyre/surface interaction over the weekend event. It should be noted how an increase in measured wet grip needs to be interpreted with respect to a race track. A decrease in measured wet grip is indicative of a track surface increasing its grip levels during racing. It is thought that complex interactions are taking place as the aggregate becomes more polished and rubber is being deposited. The result is the evolution of a green track.

8.5.2 Singapore 2017 GMM testing

Six full GMM surveys were completed of the Singapore circuit throughout the build up to the race event and after each day of the F1 event. A full GripMap survey was not possible after the F1 race as it was deemed unsafe due to heavy construction traffic. This is unique to temporary street circuits and would not be an issue at a purpose-built racetrack.

The six sets of data were analysed using frequency analysis as shown in Figure 4-15. This suggests that the overall wet grip of the entire circuit increased over the course of the event. Map 1 and Map 2 in Figure 4-15 show a similar pattern and range of values with a difference between 3a and 3b which were recorded before and after a rain storm. When compared to the GripMaps recorded after the racing days, Maps 4, 5 and 6 in Figure 4-15 show an increase in wet grip as the track is used for racing.

The GripMaps were presented on a CAD drawing of the track which was spatially aligned using the ArcMap software and georeferencing functionality as shown in Figure 5-20. The section between Turn 21 and Turn 3 is a permanent section of track and not used as a public road. It is therefore subject to little tyre/surface interaction. This area has a visibly different grip profile to that of the public highway sections between Turn 3 and Turn 16.

The different surface materials and their different ages can be discerned in the GripMaps. The straight section from Turn 5 to Turn 7 showed six distinct surface changes in the GripMaps due to different levels of grip. The areas illustrated in purple were subject to high pressure water retexturing and comprise of the areas of highest wet grip. The effect of surface treatments such as high pressure water retexturing are visible in the GripMaps. This is shown in Figure 5-23 and Figure 5-24. The grip surveys highlight the effectiveness of the treatment in preparing the surface for the race. A level of consistent, high measured wet grip is apparent in the GripMaps and the racing line can be seen to be developing in Figure 5-24.

8.5.3 Green track phenomenon at Singapore 2017

The full GMM surveys completed at the 2017 Singapore Grand Prix showed the effect of rain on measured grip. The grip levels were observed to increase after a period of heavy rain. This phenomenon has often been referred to as the track going ‘green’. The green track is then said to undergo a ‘rubbering-in’ process during a race event. As the track is trafficked, the racing line is thought to be overlaid with rubber deposits leading to higher speeds and reduced lap times.

When it rains rubber is thought to be washed away resulting in slower lap times. However, as shown in Figure 4-15 and Figure 4-16 heavy rain produced an increase in wet grip. This suggests that what is considered low grip in a road or airport context is considered as high grip in a motorsport environment. Further research into the tyre/surface interface is required to better understand this. The green track phenomena has never been assessed in in this way before.

8.5.4 Singapore 2018 GMM surveys

Full GripMap surveys were undertaken at the Singapore Grand Prix 2018. A more focused approach to the research was taken building on the learning and experience from the 2017 event. Figure 4-15 shows the cumulative frequency analysis of the GripMap data sets. A reduction of wet grip is visible from the baseline pre-event GripMap to after the race. A smaller reduction in measured grip is noted between each day of the event. In comparison to the 2017 grip data, a more consistent decline in grip is observed probably due to the track not having experienced heavy rainfall.

8.6 Evaluate the validity of the method and the output data to the motorsport industry

Grip data from a GMM survey can be displayed and analysed in a number of ways. Proposals and recommendations for the most appropriate methods of analysis were considered. The desired outcome of a surface grip evaluation is reliant on the method adopted and the analysis method selected.

8.6.1 Full GMM surveys

Chapter 5 considered how to analyse grip data. The cumulative frequency analysis was shown to be appropriate for considering large datasets of a full racetrack. It also allows grip levels for different racing circuits to be compared. It can be used to quantify grip variation or evolution for the same circuit throughout an event. The analysis method is useful but can be open to misinterpretation. The use of a GripMap is an effective method for visualising large data-sets.

The application of GIS tools to the interrogation of grip and other spatially referenced datasets development is a potential area of development. Additional datasets might include vehicle telemetry and track geometry data. For track operators or governing bodies, the ability to visualise localised areas of a track that are low in wet grip could lead to improvements in overall safety with the ability to apply targeted surface maintenance. This offers whole life cost savings to track operators while improving safety for racing drivers.

The GMM full survey offers governing bodies and race directors the ability to assess the track surface in advance of an event. Preventative maintenance can then be applied to improve areas of concern. The same data could aid tyre compound selection and tyre development. If shown during the drivers briefing, the GripMap could indicate areas of concern or potential sections with an increased likelihood of wet skidding in the case of heavy rainfall during a race.

8.6.2 Focused grip surveys using micro GripTester

The push micro GripTester CFME device was shown to produce focused grip data. The portability of the device allows it to be deployed quickly. Chapter 6 showed how it can be used to show the formation of the racing line and monitor the development of new asphalt material in terms of grip evolution. Data from the micro GripTester can be used to make a basic GripMap. This can be used to visualise grip from focused areas of interest such as a starting grid, braking associated with a corner or parts of the racing line.

8.6.3 CRP 3D model analysis

The CRP method and derived 3D models based on taking photographs of the track surface texture can be used to examine racetrack surface characteristics. Chapter 7 showed how 3D models can be used to improve understanding of grip in terms of macrotexture and other areal parameters. Data can be extracted from the 3D models and compared with grip data in order to provide a fuller understanding of racetrack surface grip and its relation to surface texture characteristics.

Improvements in mobile phone camera technology mean that expensive specialist photographic equipment is not required in order to generate viable 3D models. This has implications for use in all levels of motorsport. Amateur enthusiasts, small local racetracks and track inspectors could use the technique when assessing surface characteristics and grip.

8.6.4 Advantages of grip testing processes

Table 8 outlines the potential uses, advantages and limitations of the test methods used in this thesis. A recommendation for each method and the potential users is identified.

Table 8 Potential uses of the testing methods

Test Method	Potenial Uses	Testing Outcomes	Advantages	Limitations	Useful for
GripTester	Full grip surveys Racing line surveys Racing line surveys	full gripmaps Racing line surveys	Easy to use High quality data Easy to transport Easy to analyse data	Requires tow vehcile Expensive to ship Requies a lot of track time Uses lots of water Requires regular calibration	FIA Governing bodies Track Operators Motorsport Teams
micro GripTester	Focsed grip surveys lateral grip surveys	Useful for comparing surface changes Comparison of markings, paints or kerbs Small grip sample areas such as racing line, grid boxes or starts	Can be carried in a flight case Required little track time Easy to use Quick to analyse data	Requires regular calibration Sensitive	Motorsport Teams
CRP	In depth surface analysis Starting grids infereing tyre/surface contact	3D models 2D models	No specialist equipment required Can be done with a phone or camera Quick to analyse data	Spot test	FIA Governing bodies Track Operators Motorsport Teams

8.7 Propose a test method for the benefit of different motorsport stakeholders

It is recommended that the full GMM test method is adopted by motorsport. A full GMM survey should be a fundamental part of homogenisation of racetrack surface guidelines and legislation. A FIA/FIM surface specification that includes provision for appropriate grip level would be beneficial. The following testing schedules are proposed:

FIA Accredited Motorsport Events

- Full GMM four months before the event. This will aid with tyre choice for the event and evaluate areas of surface concern which can be addressed before the event. This can be supplemented with investigation using the CRP method. Testing ahead of events will give enough time for new patches or surface remedial works to bed in. Treatments such as retexturing can be arranged to provide a consistent surface for racing.

- Full GMM immediately before the event. This should be carried out as part of the hand over process and made available to the Race Director.
- Full GMM after the event. This will contribute to building a knowledge bank for future events. This can aid tyre compound selection, highlight areas for maintenance and improve race simulations by understanding grip evolution.
- Emergency GMM to be implemented in the event of a wet race being forecast. A racing line GripMap can be carried out with increasing depth of water film thickness to simulate the predicted rainfall severity.

FIA Track Classification

- Annual full GMM surveys as part of the FIA classification inspection. This is part of the FIA inspector visit.

Resurfacing Projects

- A full GripMap survey should be undertaken after a major resurfacing project is completed. This will be of benefit to track operators in ensuring the asphalt surface meets any required specification. Signs of early life skid resistance problems can be treated with targeted maintenance such as high pressure water retexturing.
- CRP 3D modelling; Assessment of surface texture to ensure specified material quality is met. It will also provide an indication of a surface's ability to dissipate water in wet conditions.

CHAPTER 9

CONCLUSIONS

9 Chapter 9: Conclusions

9.1 Introduction

The aim of this thesis was to better understand the variation and evolution of racetrack grip and related surface characteristics. The following conclusions address the research questions listed in Chapter 1.

9.2 Is there a need for a method to quantify grip for a racetrack?

Meetings with the FIA and leading people within motorsport identified the need for a standard method to quantify grip for a racetrack.

9.3 Can a standard method be developed to quantify and map grip on racetracks?

A review of literature found no standardised method to exist. The GripMap Method (GMM) developed and detailed in this thesis constitutes a standard method to quantify and map the grip variation for racetracks.

9.4 What are the practical applications?

The GMM test method has practical application ranging from grip evolution for a new asphalt surface to targeted remedial works. It establishes a standard method that allows comparison of circuits and assist in the racetrack homogenisation desired by the FIA.

9.5 How can the method be used to provide practical information relevant to motorsport?

Grip levels vary for different circuits due to types of surfacing and the aggregates used. A circuit has a unique signature. GMM data can be interrogated using the SQL application in ArcGIS for example in order to identify particular areas of interest. These could include particular grip thresholds and the impact of surface treatments such as high-pressure water retexturing used to improve grip.

9.6 Can the method to provide targeted grip data for localised areas of interest?

It has been shown that the GMM can be adapted to use a micro GripTester that can provide targeted grip data for localised areas of interest such as corners, starting grids, line markings, painted kerbs and areas where high friction paint has been applied.

9.7 Can tyre/surface interface parameters be related to grip?

It has been demonstrated that a range of track surface 2D and 3D areal parameters can be determined from analysis of 3D CRP texture models. These have been shown to offer new insight into the surface texture parameters related to grip at the tyre/surface interface.

CHAPTER 10

RECOMMENDATIONS FOR FURTHER RESEARCH

10 Chapter 10: Recommendations for Further Research

10.1 Develop a homogenised standard for racetrack surfaces

Meetings with the FIA established the need for a homogenised race track surface standard. Further research is recommended to establish how GMM data can contribute to that standard. The standard should include racetrack surfacing design that incorporates stakeholders' needs and is appropriate for the specific location in terms of everyday use, climate and accessible raw materials.

10.2 Explore the potential of using GMM data to improve simulations

The application of computer simulation software and driving simulators to motorsport is extensive. Increasing importance is being placed on correlation between the simulated and real environments. It is recommended that research explore how GMM data can be used as inputs to improve the modelling of the real world in this simulated environment.

10.3 Correlate GMM data and dynamic vehicle data

Geoferencing of GMM data provides an opportunity to explore its correlation with other georeferenced data from vehicles. This could include output from accelerometers, brake temperature, brake usage, tyre temperature, g-force and engine parameters. Further research is required in this area to improve understanding of grip evolution at differing time-scales and how it relates to track use.

10.4 How teams could best use GMM data to improve race performance

Motorsport teams have been measuring race track texture. How this data is used by the teams is unknown. Some teams are now starting to measure racetrack grip as the result of the research presented in this thesis. It is recommended to analyse how race teams make use of grip and other parameters.

10.5 Improve understanding of the tyre/surface interface

Further research is recommended to investigate how the low speed friction tyre/track surface interface compares to the high-speed race tyre/track surface interface.

10.6 Modelling racetrack surface using non-contact methods

Non-contact video and laser based 2D and 3D scanning systems are used on roads and runways. Further research is required to determine how this can be applied to race tracks.

10.7 Very high-speed grip

This thesis has found a power relationship between grip and speed. Research is required to assess if GMM data can be related to the very high speed of race cars and bikes.

10.8 Measuring grip in dry conditions

Top level motorsport events rarely take place in wet conditions and the industry focus is on dry grip. Better understanding and improving the ability to measure dry grip is recommended.

10.9 Improve GMM data using higher accuracy GPS

It is recommended that research be carried out to determine how RTK based GPS can be used to improve the spatial accuracy of GripTester and micro GripTester surveys.

10.10 Grip and texture related parameters

This thesis found correlation between grip and texture parameters for the GripTester and micro GripTester devices. It is recommended that further research is carried out to determine which texture related parameters offer the strongest better correlation with grip.

10.11 Race tyre enveloping at high speed

Further research is recommended to better understand how a race tyre envelopes the different scales texture scales of a surface and how this contact interface changes at high speed and around the racing line.

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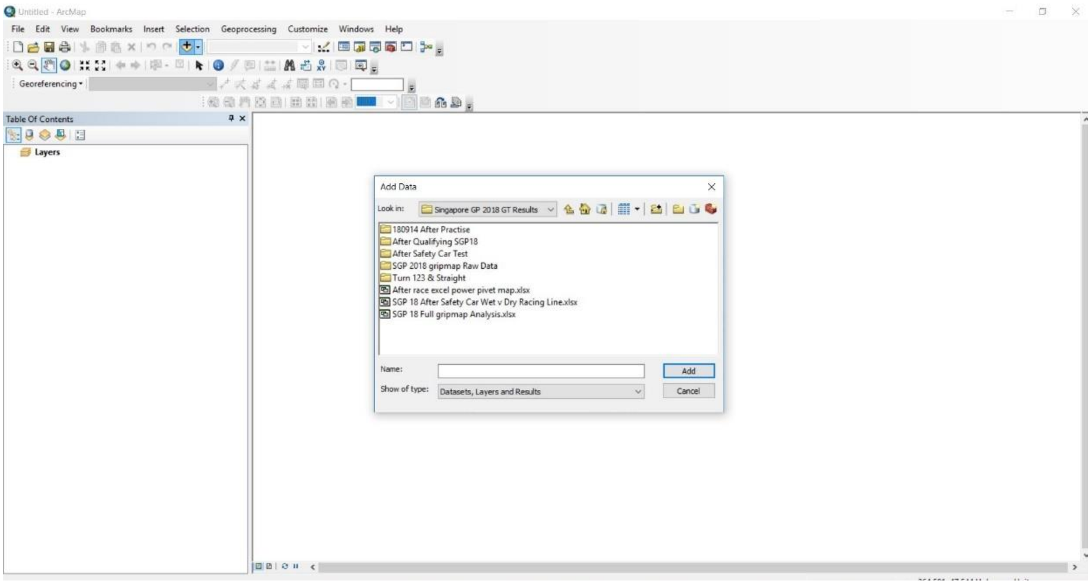
APPENDICES

Appendices

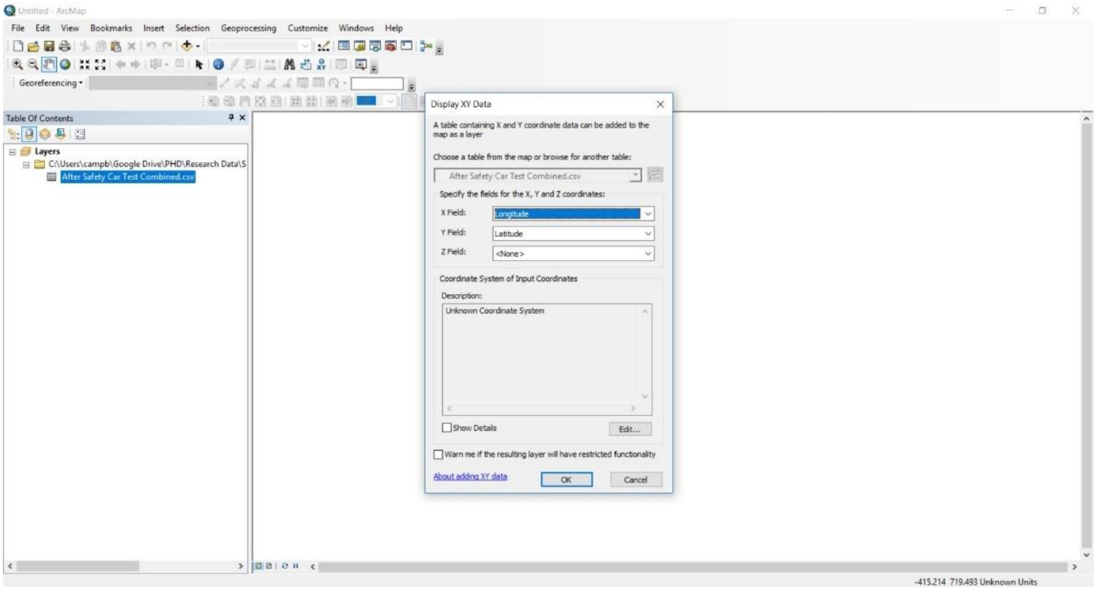
Appendix A. How to create a GripMap using ESRI ArcGIS software

The output CSV file from the GripTester, shown in Figure 5-1, must be edited before use with ArcMap. The first six rows of the .csv file containing the Roadbase© Header information needs to be removed. Row 1 of the CSV file will then contain the headers labels for each corresponding data field. Applying the 'Add Data' function allows the amended CSV file to be imported into ArcMap. The Table of Contents displays layer information.

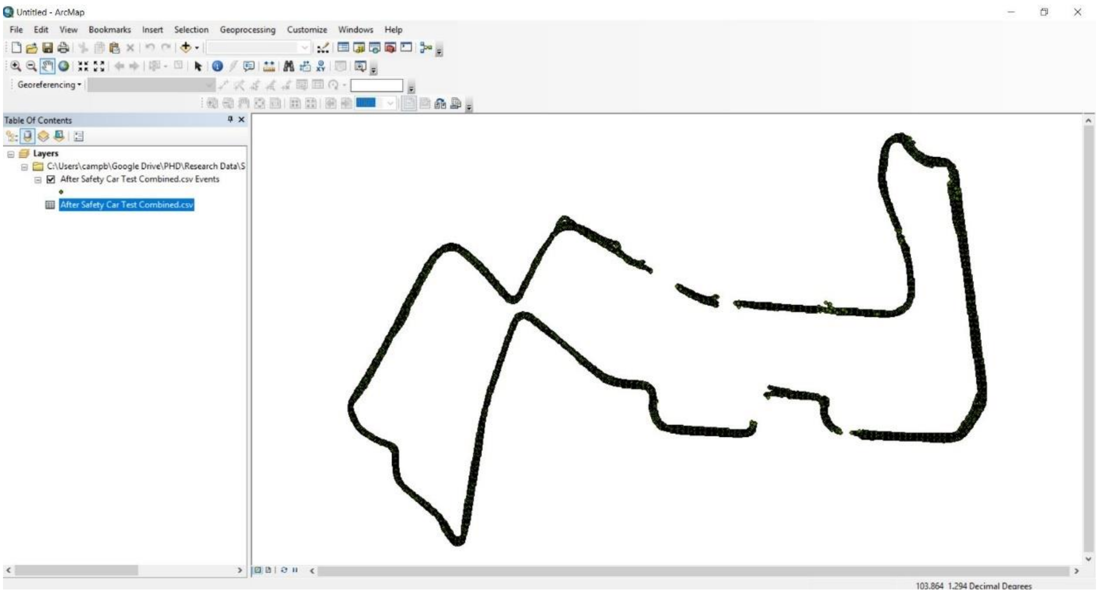


Adding data in ArcMap

Select the Layer data from the Table of Contents, right-click to activate the options menu, then select 'Display XY Data'. The Display XY Data menu allows the appropriate columns from the CSV file to be aligned with X, Y and Z axes. The correct co-ordinate system must be selected at this point.



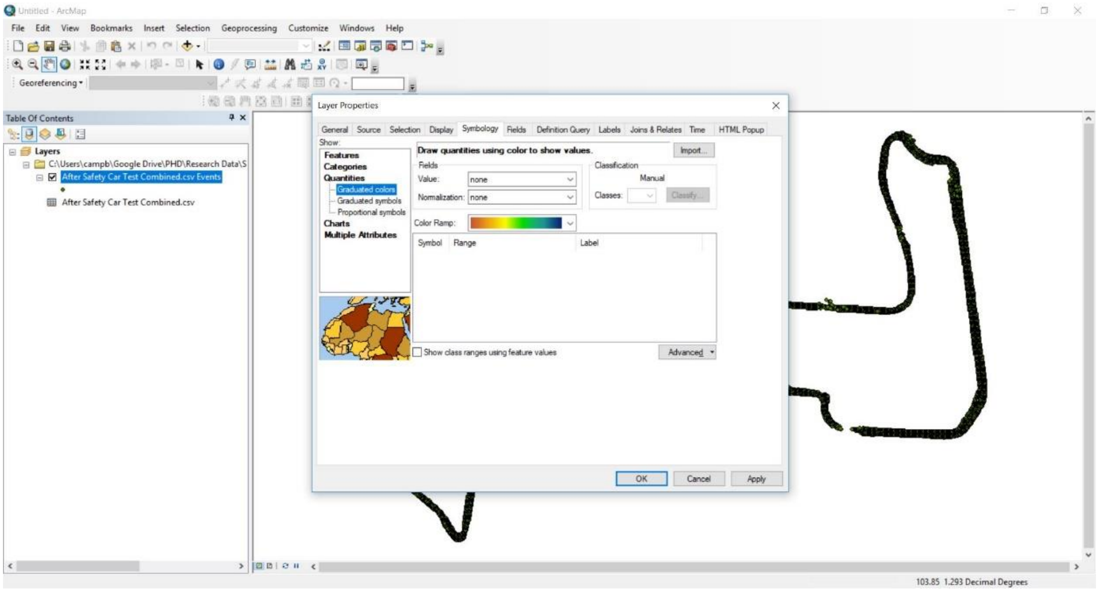
Displaying XY data in ArcMap



Georeferenced data points plotted in ArcMap

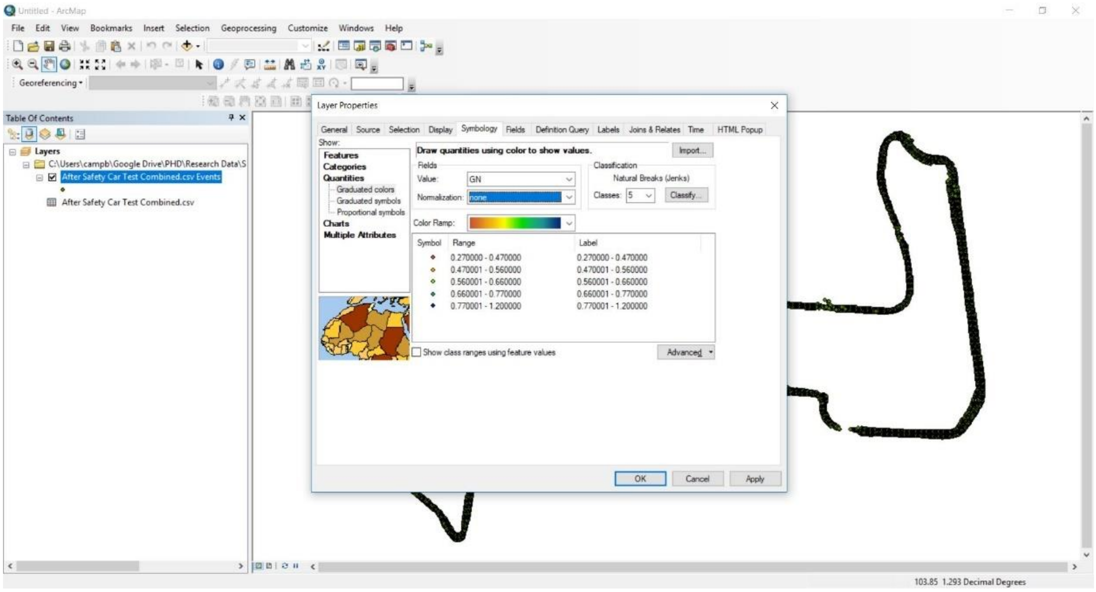
An example of the initial map drawn using the GPS data from the CSV file is shown below. This shows an outline of the Singapore track layout based on the grip survey. Select the Layer file on the Table of Contents, right-click or double click to access the Layer Properties menu. Enter the Symbology menu and select the Graduated

Colours submenu under Quantities, as demonstrated below, in order to assign threshold colours.



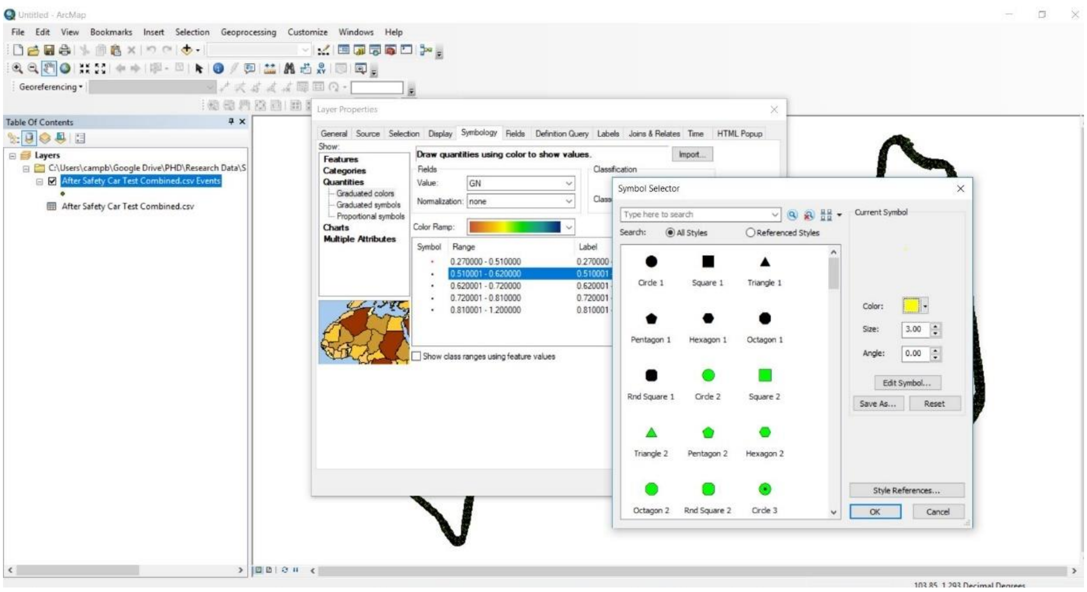
Applying colour thresholds to grip data in ArcMap

This submenu of Layer Properties contains options to display the data in different ways. The Fields Value drop down menu controls the data field that is to be displayed. The default set up when GN grip data is selected as the Field Value to display. Any column of data from the inserted CSV file can be displayed spatially. A default colour ramp is set. The default threshold range is ‘Natural Breaks (Jenks)’ which is derived from the overall dataset of the selected Field Value. Quantities can be saved and imported if a standard range is established or required. This is useful for evaluating the evolution of grip on the same racetrack with multiple GripMaps.

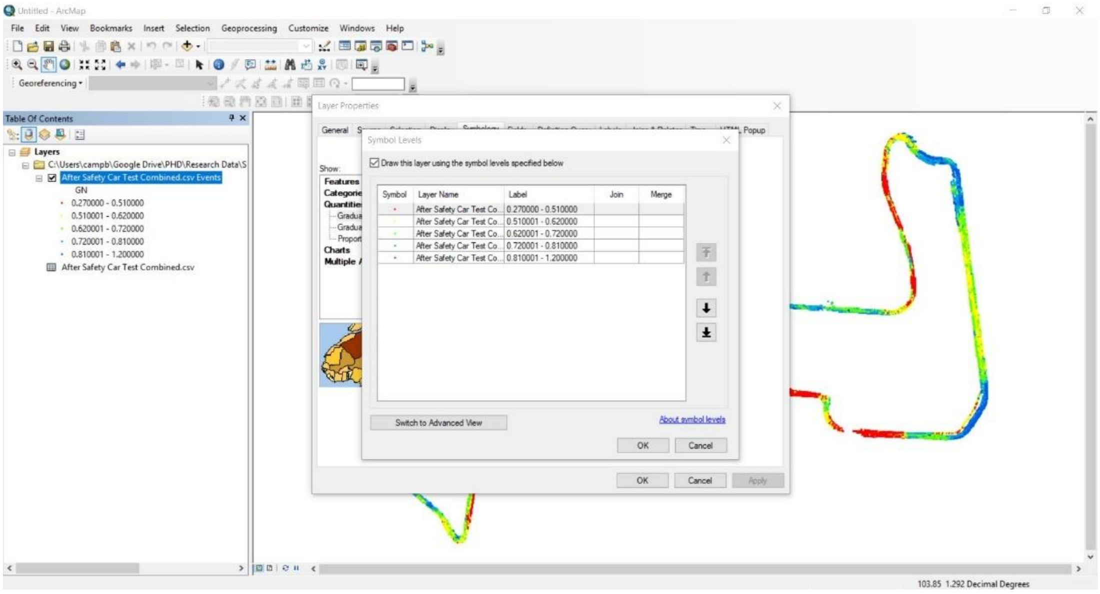


Selection of the GN Field Value

The default symbol used to display data points is a coloured disc with a black outline. This can be changed to a symbol that shows the data more clearly. The example below highlights the options and shows how the symbol icon, size, colour and angle can be adjusted. The layer can be set to show data points in a certain threshold above others if they overlap. An example of this is shown in below.

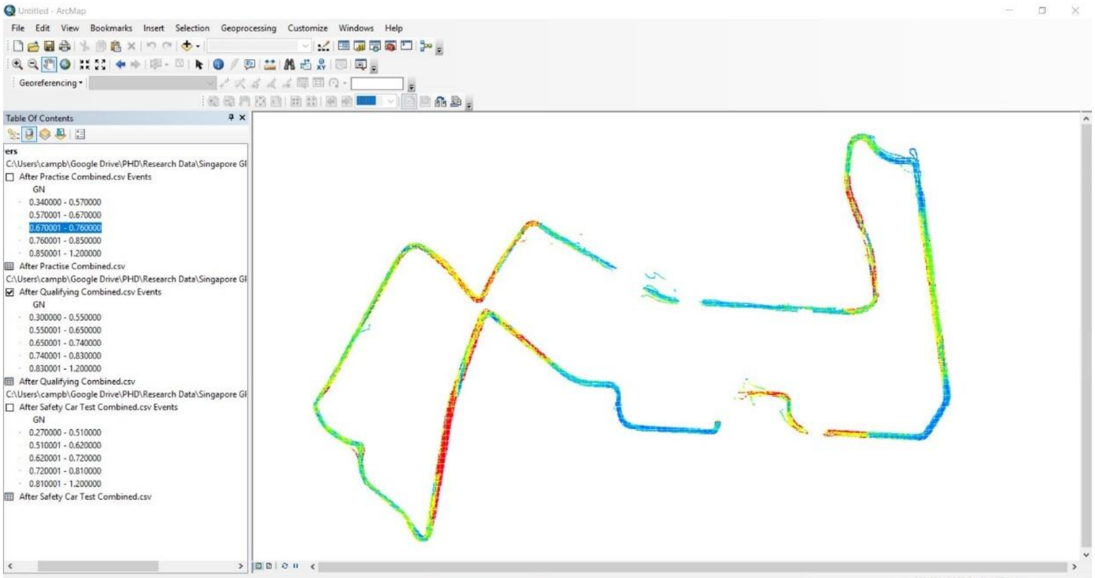


Example of ArcMap changing the Symbol to represent Field Value data points



Example of ArcMap setting priority on threshold level to display

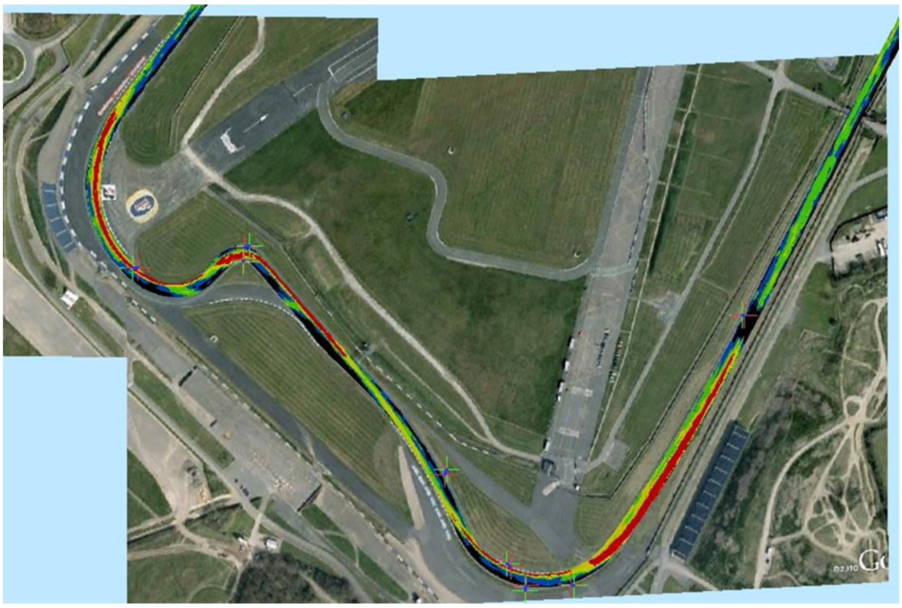
The image below shows an example of a GripMap using unfiltered grip data collected using the method outlined in Chapter 4. Survey data from other grip surveys can be added in the same way as different layers. The different GripMaps can then be quickly compared in one composite map. An example of multiple GripMaps in layers listed by source is shown below.



Multiple GripMaps in ArcMap listed by source

Georeferencing a GripMap to a base map layer

ArcMap allows a map layer to be georeferenced to facilitate the use of a base map. Adding a base map allows a GripMap to be spatially aligned with points of interest contained in the base map. Base maps can include Computer Aided Design (CAD) drawings, Google Maps, and Google Earth images. An example of a GripMap created using ArcMap georeferenced with a base map from Google Earth is shown below.



GripMap over georeferenced Google Earth image

An example of a GripMap created using the georeferencing tools in ArcMap aligned to a CAD drawing is show below. The CAD drawing was supplied by Singapore Grand Prix management (SGP). The GripMap data displayed in this manner allowed SGP management to target track surface maintenance to areas of lower grip.

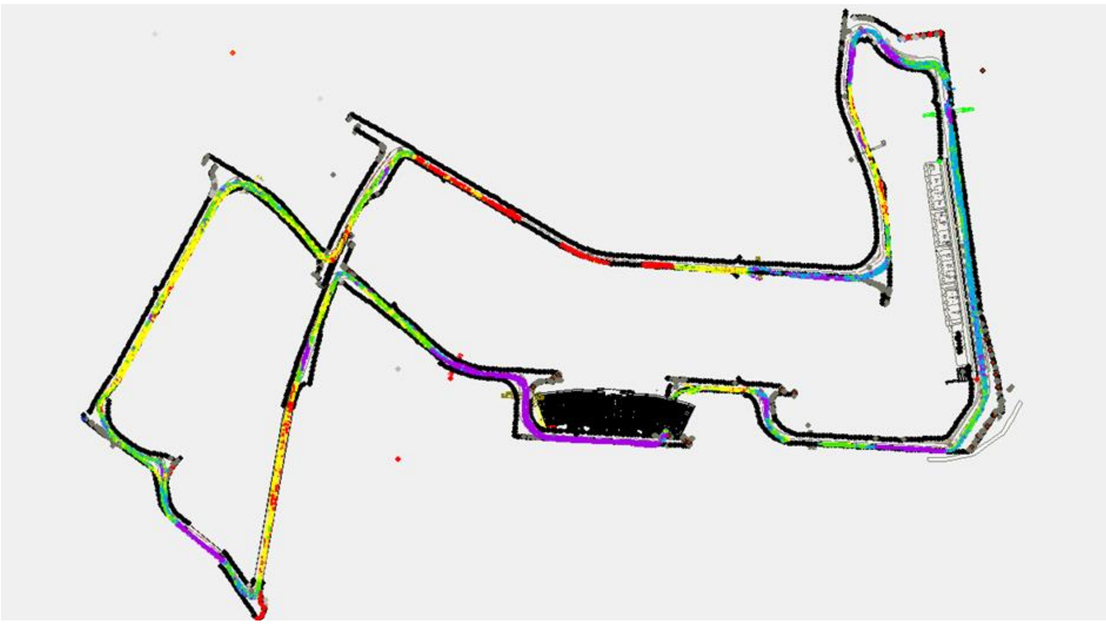


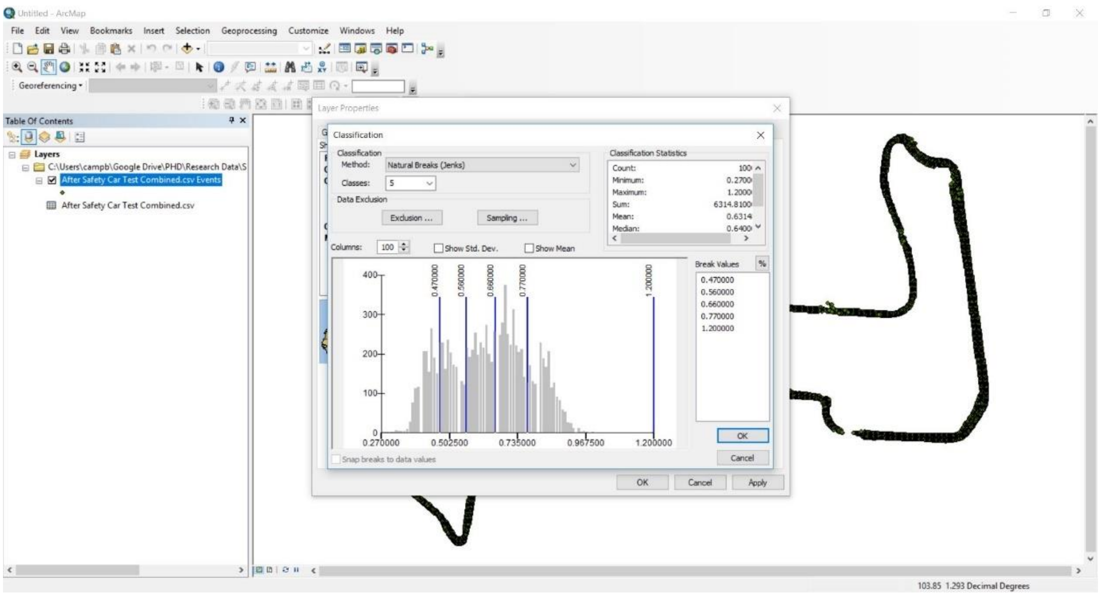
Figure 0-1 GripMap georeferenced to a CAD drawing for SGP circuit.

Application of different thresholds to GripMaps

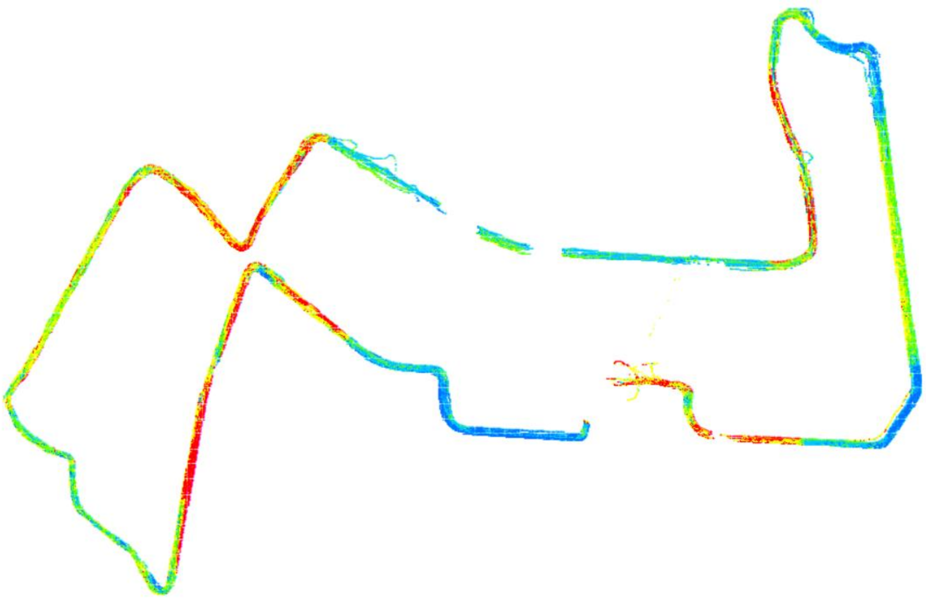
The threshold ranges available in ArcMap can be customised depending on the specific characteristics of the dataset being analysed. The classifications applied can be user defined or selected from a set of statistical analysis tools available in ArcMap. The image below shows selection of 'Classify' to open up the Classification menu screen.

The GripMap shown below was generated with threshold ranges based on the Jenks Natural Breaks classification method. This method aims to maximise the variance between the threshold ranges and reduce the variance between the ranges (Jenks, 1967). The threshold ranges applied to the overall data set are shown below.

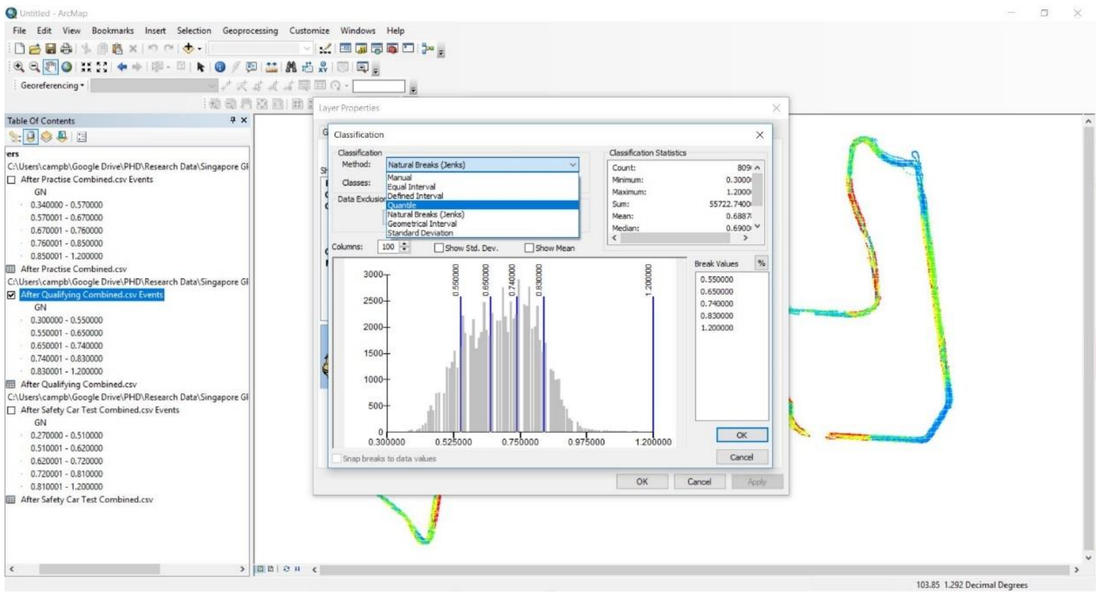
The following screenshots present examples of how ArcMap can calculate different statistical classifications from the field dataset being displayed. The selected threshold ranges can affect how the data is displayed.



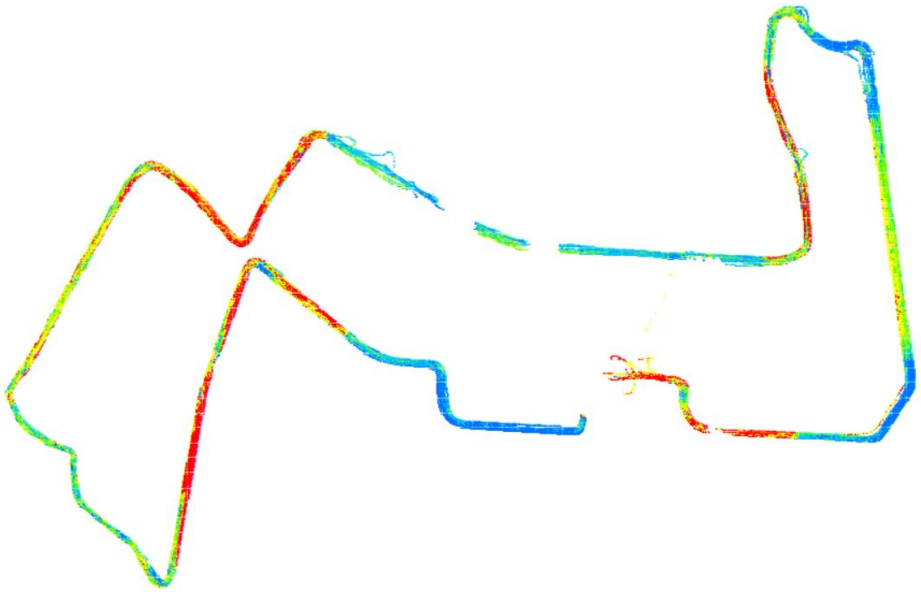
Application of the Natural Breaks (Jenks) option for thresholding grip data (Jenks, 1967)



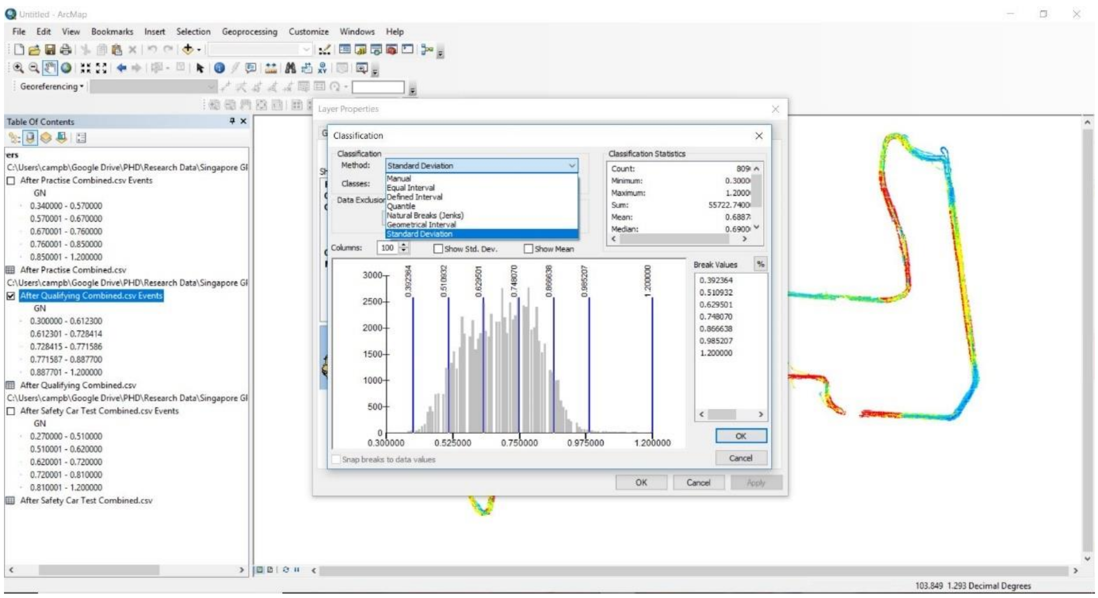
GripMap classified using the Natural Breaks (Jenks) surface optimisation algorithm (Jenks, 1967)



GripMap classified based on quartiles

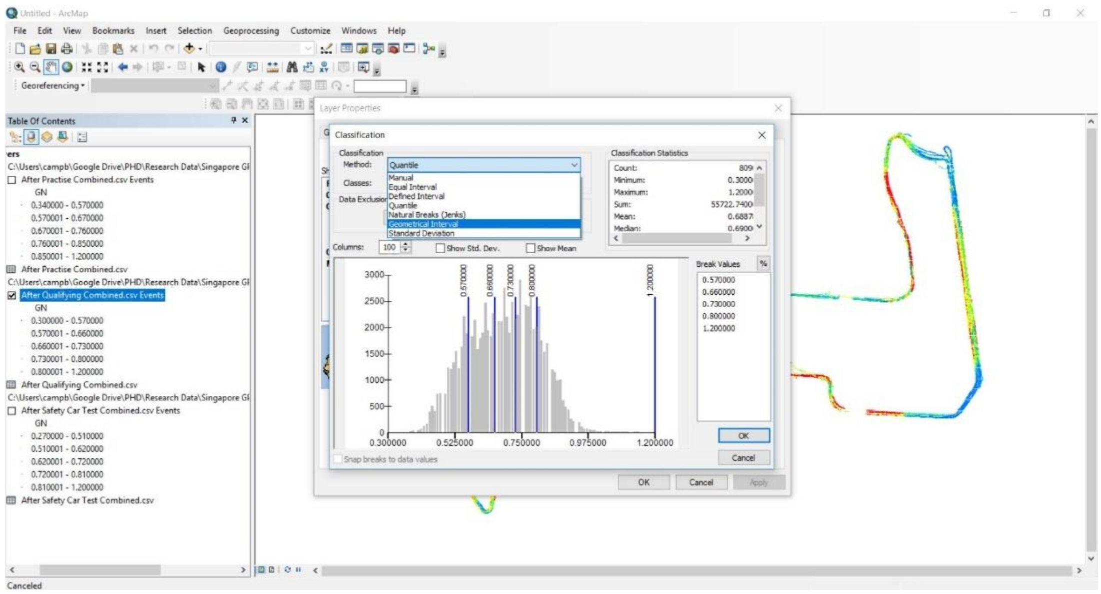


GripMap classified based on quartiles

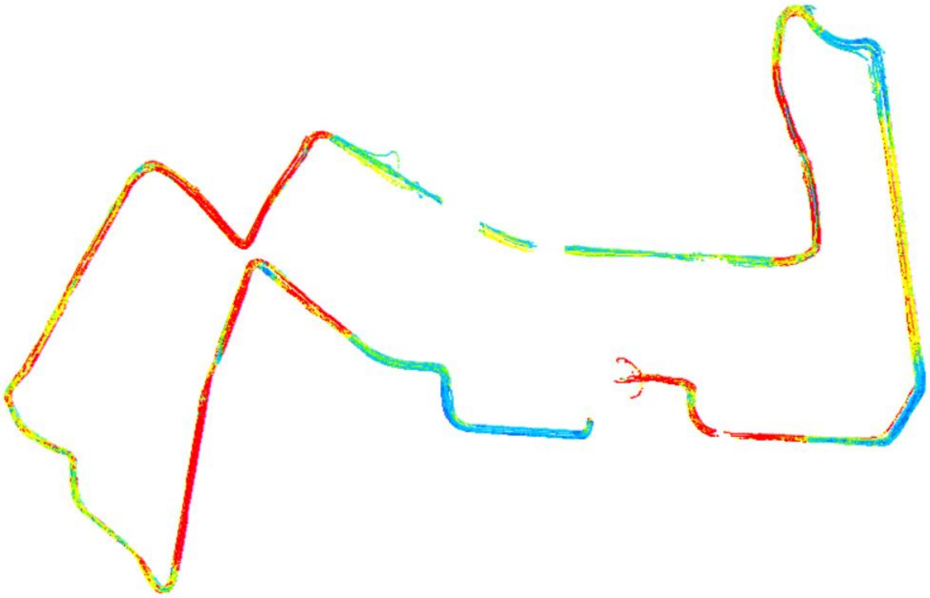


Classification based on Standard Deviations

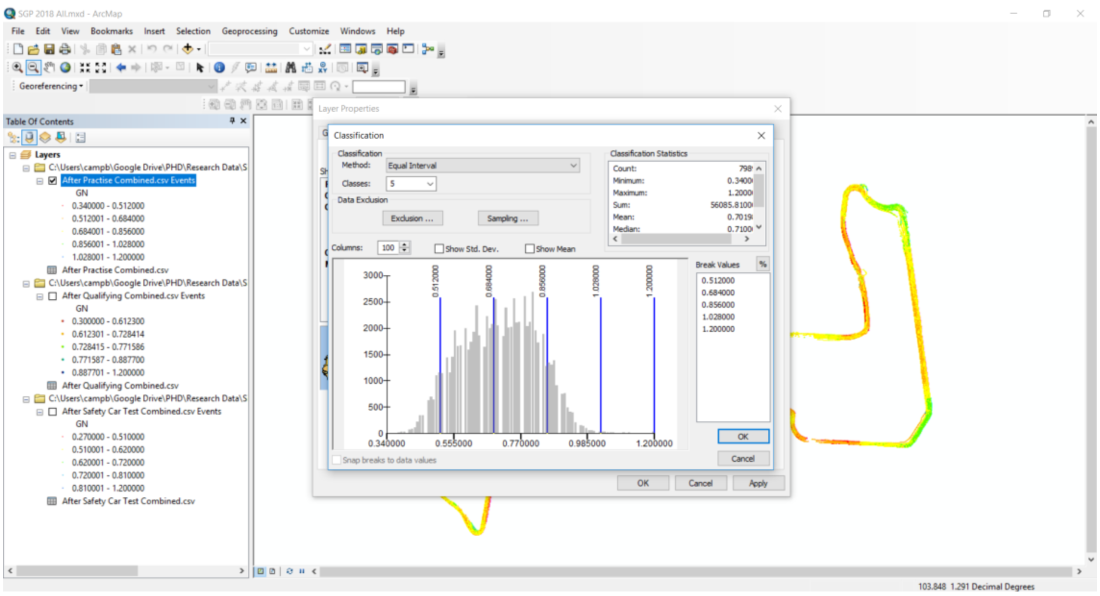
Classification based on Standard Deviations



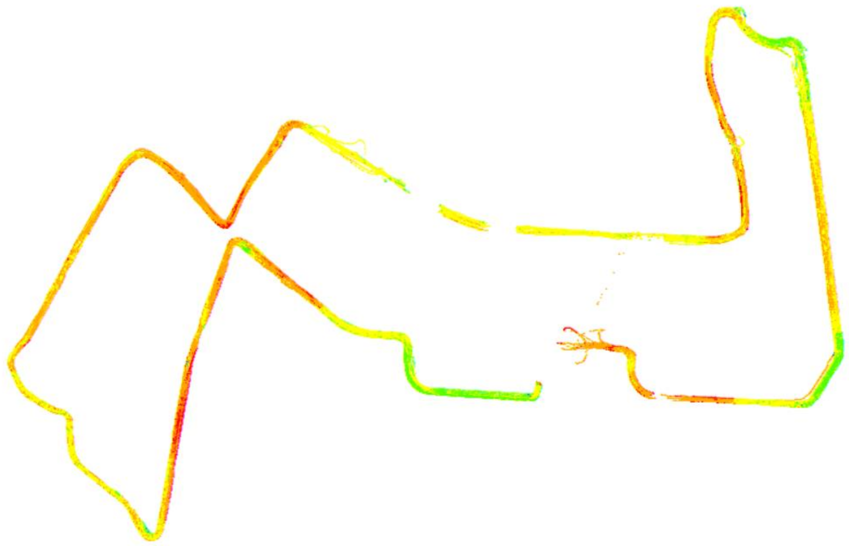
Classification based on geometrical intervals



Classification based on geometrical intervals



Classification based on user-defined equal intervals

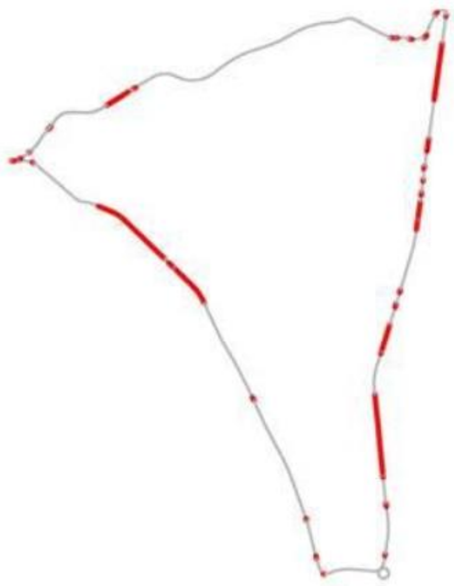


Classification based on equal intervals

Varying the threshold ranges can highlight patterns in the grip data arising from small variations in tyre/surface contact in a high grip dataset. Care is required when visually comparing GripMaps to ensure that the same classifications have been applied to all the datasets.

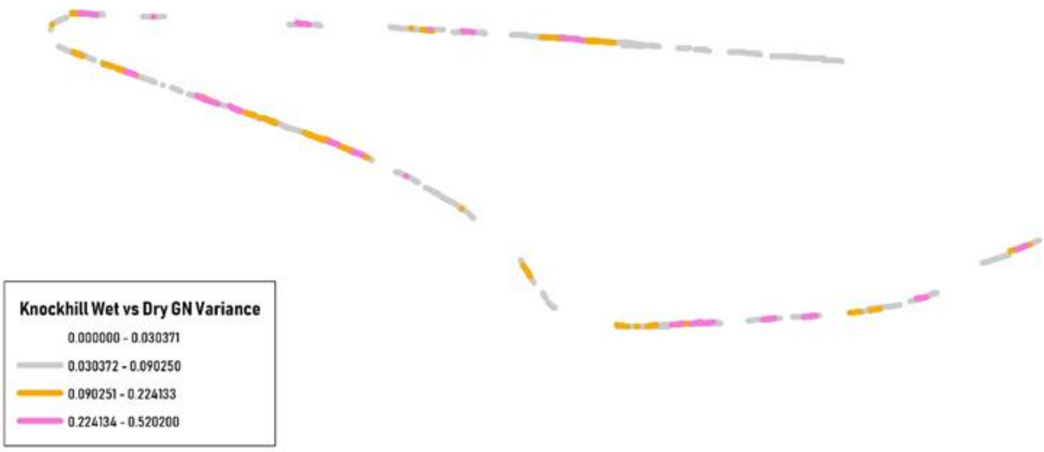
Querying GripMap data sets

ArcMap has the ability to query grip and other types of spatially referenced data using SQL queries. Simple queries such as 'show all grip data that is less than or equal to 0.4GN' can be quickly executed. A grip level of 0.4GN would be considered low grip on a standard single carriage way road (DRMB HD28/15, 2015). Woodward et al (2012) demonstrated this as shown below.



Grip data plotted using GIS showing areas where wet grip is less than 0.4 (Woodward et al., 2012)

The image below shows how the difference between wet grip and dry grip from two single lap surveys of the racing line can be compared using ArcMap. The geodatabases from both surveys were combined. A query was run to identify intersecting data points using the GPS data from each survey. Once these were highlighted, a query was run to calculate the difference in grip between the intersecting dry grip data with the wet grip data.



Difference in grip between the intersecting dry grip data with the wet grip data

Appendix B. Map of Singapore Grand Prix Marina Bay Circuit including corner numbers. (Restu20, 2015)